



# **TSP---A Collection of FORTRAN Programs for Processing and Manipulating Time Series**

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# TSPP---A Collection of FORTRAN Programs for Processing and Manipulating Time Series

By David M. Boore<sup>1</sup>

## Introduction

This report lists a number of FORTRAN programs that I have developed over the years for processing and manipulating strong-motion accelerograms. The collection is titled **TSPP**, which stands for **T**ime **S**eries **P**rocessing **P**rograms. I have excluded “strong-motion accelerograms” from the title, however, as the boundary between “strong” and “weak” motion has become blurred with the advent of broadband sensors and high-dynamic range dataloggers, and many of the programs can be used with any evenly spaced time series, not just acceleration time series.

This version of the report is relatively brief, consisting primarily of an annotated list of the programs, with two examples of processing, and a few comments on usage. I do not include a parameter-by-parameter guide to the programs. Future versions might include more examples of processing, illustrating the various parameter choices in the programs.

Although these programs have been used by the U.S. Geological Survey, no warranty, expressed or implied, is made by the USGS as to the accuracy or functioning of the programs and related program material, nor shall the fact of distribution constitute any such warranty, and no responsibility is assumed by the USGS in connection therewith.

The programs are distributed on an “as is” basis, with no warranty of support from me. These programs were written for my use and are being publically distributed in the hope that others might find them as useful as I have. I would, however, appreciate being informed about bugs, and I always welcome suggestions for improvements to the codes. Please note that I have made little effort to optimize the coding of the programs or to include a user-friendly interface (many of the programs in this collection have been included in the software **usdp** (Utility Software for Data Processing, <http://www.usdp.org/>), being developed by Akkar et al. (personal communication, 2008); **usdp** includes a graphical user interface). Speed of execution has been sacrificed in favor of a code that is intended to be easy to understand, although on modern computers speed of execution is rarely a problem.

I will be pleased if users incorporate portions of my programs into their own applications; I only ask that reference be made to this report as the source of the programs.

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## Revisions: v 1.6

This version contains revised versions of a number of the programs, as well as a useful new program---*filt\_plot.for*. A new sample session (Session 3) is included to highlight the use of this new program in choosing low-cut filter corner frequencies.

## Some Abbreviations

I occasionally use abbreviations, particularly in the descriptions of the programs. For the convenience of the reader I define the abbreviations here:

**Table 1.** Abbreviations.

Abbreviation	Meaning
FAS	Fourier amplitude spectrum, usually of acceleration
FFT	Fast Fourier Transform
FS	Fourier amplitude spectrum
PGA	peak ground acceleration
PGD	peak ground displacement
PGV	peak ground velocity
PSA	pseudo-absolute response spectral acceleration ( $\omega^2 SD$ )
PSV	pseudo-relative velocity response spectrum ( $\omega SD$ )
RS	response spectrum (type unspecified)
SA	absolute acceleration response spectrum
SD	relative displacement response spectrum
SV	relative velocity response spectrum
sps	samples per second
zoc	Zeroth-order corrected time series (in which the only baseline-correction consists of a mean being removed from the time series, the mean usually determined from the pre-event portion if available or the whole record if not available).

## Program Acquisition and Use

*Acquiring:* The programs can be obtained from the online-publications link on my web site (<http://quake.usgs.gov/~boore>). The programs are contained in several compressed binary files ("zip" files). This report and the file containing the SMC format specifications (discussed below) are in TSPP\_DOCUMENTATION.ZIP. The source code is in four files: TSPP\_CONVERT\_FOR.ZIP, TSPP\_PROCESSING\_FOR.ZIP, TSPP\_UTILITIES\_FOR.ZIP, TSPP\_SUBROUTINES\_FOR.ZIP, the control files are in TSPP\_CONTROL\_FILES.ZIP, the executables, compiled to be run on a PC, are in TSPP\_CONVERT\_EXE.ZIP, TSPP\_PROCESSING\_EXE.ZIP, and TSPP\_UTILITIES\_EXE.ZIP, and the data used in the sample sessions are in TSPP\_DATA\_FOR\_SAMPLE\_SESSIONS.ZIP.

*Compiling and linking:* The programs use "include" statements to bring in the subroutines. These include statements assume that the subroutines are in a folder titled "\forprogs", located in the same letter drive as the programs. The programs are written in FORTRAN 77, with some Fortran 90 extensions. I compiled and linked the programs using Lahey/Fujitsu LF95.

*Using:* All programs are used from a command prompt window (see **usdp** for a Windows version). Most of the programs use a control file so that processing can be done in a batch mode, working with a list of files. It is convenient to make the file list using the DOS command "dir/on/b [*specify file, using wildcard character \* if necessary*] > file.list". Note that the "b" switch produces a brief listing, without file sizes, creation dates, and so on; the /on switch is optional, and will order the files alphabetically. Using /o-d will order the files by date and time, with the most recent being first; this is often useful if there are many files in a folder and only the most recent are to be used. For example, to make a list of all files in the current folder (named "working\_folder" in this example) with the extension "smc" and containing the string "\_u" in the file name, use the following command in the Command Prompt window:

```
C:\working_folder> dir/on/b *_u*smc > file.list
```

The file *file.list* will contain a list of files that can be pasted into the appropriate control file.

This is not a User's Guide to the programs. For details of program capabilities and use, start by reading the brief annotations in the following tables, then read the comments at the beginning of each program, and also read the comments in the corresponding control file. It may also be useful to read the dated list of program modifications included at the bottom of the header comments at the beginning of each program file. I have included several examples of processing, from which the user can obtain some information that will help in using the programs.

Some comments and examples regarding processing can be found in a few of my papers, including those in the references at the end of this report.

## Data Format

The processing programs read and write files that are in the standard SMC format used for the accelerogram data distributed by the Strong-Motion Program of the U.S. Geological Survey (USGS) (<http://nsmp.wr.usgs.gov/smcfmt.html>) except that I have utilized one of the undefined integer header values (47) to allow an option for the higher precision now available with modern dataloggers (see the file SMCFMT\_DMB(V.1.0).PDF for a description of the modified format). The SMC-format files are in ASCII, with text, integer, and real headers, followed by a block of comments, and then the data. The headers and comments allow many of the metadata for a time series, including details about the processing, to be carried along with the time series values. The data are stored in line-oriented format (a number of consecutive data values per line, wrapped to following lines as needed).

Although other formats for strong-motion data are in use, such as COSMOS V1 ([http://www.cosmos-eq.org/menu/2\\_Publications/cosmos\\_format\\_1\\_20.pdf](http://www.cosmos-eq.org/menu/2_Publications/cosmos_format_1_20.pdf)), as of this writing the USGS is still distributing data in SMC format, so I have not added conversions to the more recent formats. Note, however, that TSPP includes a collection of programs to convert data files in

various formats into SMC format. These reformatting programs are grouped into three sets: those dealing with generic data formats, those with agency-specific formats, and one program for creating simple time series (such as a box, a spike, or a portion of a sinusoid) in SMC format.

## Programs

This collection contains many programs that are designed to operate on SMC-format files as objects (not to be confused with object-oriented programming, but as opposed to a user having to explicitly open each file and read the contents to extract the data.). Not all of these programs are as thoroughly vetted as others. Some of the programs were written for a special use and have been used rarely, while others make up the workhorses of the collection---these include, but are not limited to, **asc2smc**, **blpadflt**, **smc2fs2**, **smc2rs**, **smc2vd**, **smc2asc**, and **smctsplt**. In the tables below I have highlighted in yellow those programs that I use most often (lack of highlighting does NOT mean that the other programs are not useful, only that I use them less often). A warning: I don't always update all programs that perform similar functions, so when an alternative exists to perform a certain operation, use the more recent program (when in doubt, consult the dated list of program changes in the headers to the program file). I include all of the programs in the collection more as a convenience for me than for the user. I hope that the yellow highlighting will help the user sort through the collection.

I have organized the programs into four sets:

1. Programs that convert data in various ASCII formats into SMC-formatted files; also included in this set is a program for generating files with simple waveforms for testing purposes.
2. Programs that process the SMC files to create new SMC files with the modified time series, or to compute other measures of ground shaking. Some of the programs work with a single time series, and others work with a pair of time series.
3. Post-processing and utility programs to accomplish a variety of tasks, such as changing header values in the SMC files (e.g., **smcnuhdr**), or combining a mix of time series, response spectra, and Fourier spectral SMC files into a single file with columns containing time, amplitude, period, response spectra, and/or frequency, and Fourier amplitude spectra (**smc2asc**). The output file written by **smc2asc** can be imported easily into a variety of programs for further analysis or to make plots. Some of the programs in this group could logically be placed into the first group. Examples are the program **smc\_rot** that rotates two time series to generate a new time series, or the program **smc\_snip** that snips out a segment of specified duration and starting time from a longer time series.
4. Subroutines. The subroutines used by the previous programs are collected into this group. As before, some are used often, some rarely.

Because it is understood that the output of the programs will be a file or files, I rarely mention this in the tables below. The programs produce output in either SMC format or in column-oriented format (some programs have the option of saving in either format). Column-oriented format arranges consecutive values of the dependent variable in columns, unlike the line-oriented format of SMC files. The collection of post-processing and utility programs contains one very useful program---**smc2asc**---that converts a series of SMC files into a single ASCII file with



columns of time (or frequency or period, depending on type of data) and dependent values, a pair of columns for each SMC file. These column-oriented ASCII files can then be easily imported into standard graphics programs for plotting or subsequent manipulation.

### Data Conditioning (Formatting and Conversion)

The programs for reformatting data written with generic formats are:

**Table 2.** Programs for generic formats.

Program Name	Program Description
asc2smc.for	Create an SMC file from an ASCII file in which the data are in two columns: time, data
onecol2smc	Create an SMC file from an ASCII file in which the data are in one column, with the samples per second specified in the control file
wrapped2smc.for	Create an SMC file from an ASCII file in which the data are in a block with a known format (e.g., (10f8.2)).

The programs for reformatting data written with agency-specific formats are in the following table. I have specified the agency for some of these programs.

**Table 3.** Programs for agency-specific formats.

Program Name	Agency Name
bdsn2smc.for	Berkeley Digital Seismic Network
cgs2smc.for	California Geological Survey
cr2gs.for	USGS-Central Region
cwb2smc.for	Central Weather Bureau (Taiwan)
esmd2smc.for	European Strong-Motion Database
evt2smc.for	Kinematics EVT format files
f96_2smc.for	
impc2smc.for	Imperial College (England)
iran2smc.for	
knet2smc.for	K-Net (Japan)
nga2smc.for	
pea2smc.for	Pacific Engineering Associates
sac2smc.for	SAC format
sce2smc2.for	S. Cal. Edison
smc_uneven2even.for	
smcu2evn.for	
sxv2smc.for	Spudich and Xu Compsyn
taiwan_one_component2smc.for	
uca2smc.for	UCA (San Salvador)
upsar2smc.for	

usc2asc.for	University of S. California
uscv1gs.for	University of S. California
uscv2gs.for	University of S. California
uscv3gs.for	University of S. California
uw2gs.for	University of Washington
evt2smc.for	Kinematics files in evt format

The program for making “test” time series consisting of simple waveforms is listed below:

**Table 4.** Program to make “test” time series.

Program Name	Program Description
smc_make.for	Make a spike, pulse, step, ramp, n cycles of sine, or noise in SMC format

## Processing Time Series

**Table 5.** Processing programs.

Program Name	Program Description
<b>General Purpose</b>	
blpadflt.for	The main processing program. It can do baseline corrections, filtering, integration to velocity and displacement, and computation of response spectra.
filt_plot.for	Applies a suite of filters and plots the unfiltered acceleration, zeroth-order-corrected (zoc) velocity, and filtered displacements for a suite of filter corners, on a single page. In combination with smc2fs2, this program is particularly useful in helping decide what filter corner frequencies to choose in processing the data.
<b>Filter</b>	
smc_flt.for	Apply filtering to the time series within a list of SMC files; I recommend using blpadflt instead.
smc2cav	Compute the Cumulative Absolute Velocity (CAV)
<b>Integrate and Differentiate</b>	
smc2vd.for	Integrate an acceleration time series to velocity and displacement.
smc_d2va.for	Calculate acceleration and velocity from displacement.
smc_v2a.for	Calculate acceleration from velocity.

smc_v2ad.for	Calculate acceleration and displacement from velocity file.
smc2husd.for	Calculate the cumulative integral of square acceleration from acceleration file (use to make Husid plots).
smc2jerk.for	Calculate jerk (the first derivative of acceleration).
<b>Envelope of Time Series</b>	
smc2env.for	Use the FFT to compute the envelope of a time series. Store the result in a column-oriented file.
<b>Fourier Spectra</b>	
smc2fs2.for	Compute the Fourier amplitude spectra for a specified time series. Smoothing options and different ways of specifying frequencies are included. Output can be in SMC or column-oriented format.
smc2fas.for	Compute the Fourier amplitude spectra for a specified time series. Less general than smc2fs2.
smc2fs2_complex.for	Compute the Fourier complex spectra for a specified time series. A special purpose program; not well tested.
smc2phs.for	Compute the Fourier amplitude, phase, and phase derivative (see Boore, 2003b).
<b>Response Spectra</b>	
smc2rs.for	Compute SD, PSV, pseudo-absolute PSA, SV, and SA response spectra.
smc2rds.for	Compute the time-domain response of an oscillator to an input acceleration
smc2rs_sel_per.for	Compute RS for selected periods, writes the result to a single-column file, one record per line, along with the latitude and longitude of the station, and the distance from a specified location (such as an epicenter).
smc2rs2.for	Compute RS and write as an SMC-format file; less general than smc2rs.
smc_acc2psa_vs_r.for	Similar to smc_psa_vs_r, but allows filtering of the input time series before computing the PSA.
smc_psa_vs_r.for	Compute PSA; write into a file along with distance from a multi-segment fault.
smc2psa_sd_pgv_pga.for	Compute PSA, SD, PGV and PGA for a list of files.

<b>Operations Using Pairs of Time Series</b>	
smc_acc2psagm_vs_r.for	Similar to smc_psagm_vs_r, but allows filtering of the input time series before computing the PSA.
smc_psagm_vs_r.for	Compute geometric mean of PSA from two components; write into a file along with distance from a multi-segment fault. No rotations are performed.
gmrot50.for	Compute the geometric mean of the two horizontal components for a series of rotation angles. This version has less output than gmeanrot; it computes the measures discussed in Boore et al. (2006). <b>This program has been superseded by smc2psagmrot.</b>
gmeanrot.for	Compute the geometric mean of the two horizontal components for a series of rotation angles.
smc2psagmrot.for	Compute the geometric mean of the two horizontal components for a series of rotation angles. This version prints out the PSA of each individual as-recorded component, the geometric mean of the two as-recorded components, the maximum and minimum PSA and geometric means over all angles of rotation, GMRotD50, GMRotI50, and PGA, PGD corresponding to the angle of GMRotI50, as well as the angle used to obtain GMRotI50.
smc2gm_ar.for	Compute the geometric mean of two as-recorded (no rotations) horizontal components, as well as the response spectra of each individual component, and the larger of the two components.
smc2gmn.for	Compute the geometric mean of the two horizontal components for a series of rotation angles. Output minimum, maximum, and fractile values of the geometric mean for specified periods. Used in preparing Boore et al. (2006)
smccoher.for	Compute the coherence between two SMC files.
smccorrl.for	Cross correlate two SMC files using a specified range of lag times.
smexcorr.for	Cross correlate up to 10 pairs of files and write results as columns in a single file.
smcinty1y2.for	Produce a file of the cumulative integral square of two time series

<b>Miscellaneous (Mostly Older) Programs</b>	
blftsegs.for	Integrate to velocity, fit a series of line segments to the velocity, subtract the slopes of the line segments from the acceleration and write a new, baseline-corrected file.
fasratio.for	Compute the ratio of Fourier amplitude spectra for pairs of time series in SMC format.
smc2subd.for	Read an SMC filename from a control file, compute PSV, and write it to a file in the same format as Gail Atkinson's SUBALL.DAT.
samaxmin.for	Loop over a series of rotation angles, for each forming the time series for the rotation angle and computing PSA. The maximum and minimum over the set of rotation angles is output (an older program).

## Post-Processing and Other Utility Programs

**Table 6.** Programs for post-processing and other tasks.

<b>Program Name</b>	<b>Program Description</b>
<b>Plot SMC time series</b>	
smctsplt.for	Plot up to 31 time series on a single page. A very useful program.
<b>Convert from SMC to ascii</b>	
smc2asc.for	Combine up to 72 SMC files into a formatted, single-column file. The SMC files can be a mix of time series, Fourier spectra, and response spectra. Time-shifting, amplitude scaling, and decimation can be included.
rs2_col.for	Read a list of rs2 files and print out col files for use in plotting.
<b>Edit SMC headers</b>	
smcnuhdr.for	Replace integer and real headers in SMC files with specified values.
smcaddeq.for	Read earthquake name from control file and write into the appropriate SMC text header (4, columns 27:80).

smcaddsn.for	Read station number from appropriate SMC text header (3, col 1:4), verify that it is non-blank and an integer in the range 0-9999, and if so, then write into int_header(30).
smcfxhdr.for	Add header information to SMC files (primarily text headers).
smc_add.for	Read station name from control file and write it in text header(6)(11:40), obtain orientation from text header(6)(53:57) and write the appropriate number in the integer headers 13, 14.
smc_long.for	Change sign of station longitude and earthquake longitude to negative (if positive) (this program was written to overcome a provincialism in some older accelerogram data from areas of west longitude, for which positive values were stored for the longitude).
add_vs30_2smc	Add vs30 to smc file real_head(40)
<b>Obtain information about SMC file</b>	
smc_info.for	Read a list of SMC or RS2 files, and for each, extract station information and print it to two files: 1) a summary file; and 2) a file in comma-delimited format for import into data base programs.
smc_hdrs.for	Read a list of SMC file names, and for each entry, open the data file and read the header information. The extracted information is then written to a file. This eliminates the need to manually list the contents of each file to check components, station coordinates, and so on.
smc_sta.for	Read a list of SMC files, and for each, extract station information and print it to two files: 1) a summary file; and 2) a file in comma-delimited format for import into data base programs.
smc_ylym.for	Get initial value (y(1)) and peak value of time series
<b>Make new SMC files</b>	<b>Does not include filtering, integration, and differentiation operations---see the section on processing programs for these operations</b>
smc_snip.for	Snip out a section of an SMC file and write the results as a new SMC file.
smc_rot.for	Rotate pairs of SMC files by a specified angle, resulting into two new pairs of time series.
smc_rot_1pair_per_azm.for	Rotate pairs of files, where each pair, the azimuth, and the output file names are specified separately (corresponds to an old version of smc_rot.for, but it may be useful in some situations).
smc_pad.for	Add leading zeros to SMC file and write as a new file.

smc_std.for	Snip out a section of an SMC file and compute the mean and standard deviation.
smcadd2.for	Read two SMC files and adds one to another, time step by time step, to create a third file.
smcoffst.for	Read in a SMC file, apply a specified offset, and write as a new SMC file. The intent is to mimic a digitizer that does not have a perfect 0.0 baseline.
smcrmvsn.for	Remove a single cycle of a sine from acceleration. This is to study Norm Abrahamson's "fling-step" (personal communication, 2003).
smcervse.for	One-time-use program to time-reverse an SMC file (to confirm that acausal filtering is blind to the time direction).
smcxtend.for	Extends a SMC file by either adding zeros to front and back or by reflecting the time series around the beginning and ending points (a special purpose program, written while preparing Boore, 2005b).
smcintpr.for	Interpolates an SMC file to finer spacing, using an FFT with zeroes added above the Nyquist frequency.
smcintprdp.for	Double precision version of smcintpr.for
smc_dig.for	Simulate analog-to-digital conversion, and write as a new SMC file. Used for Boore (2003a).
<b>Post-process results of main processing programs</b>	
band_avg.for	Compute averages of spectra between specified bands.
env2avg.for	Read a series of files containing envelopes (made by env2phs) and compute the average of the envelopes.
env2hist.for	Read a series of files containing envelopes (made by env2phs) and compute an average histogram.
fas_avg.for	Read a column-oriented file made by smc2fs2 and compute and output the average and standard average of the mean, using linear averages.
fs2_avg.for	Read up to 72 Fourier amplitude spectra in SMC format and reformat to produce a column-oriented file, including the average of the spectra.
lfhf_avg.for	Read a column-oriented file made by blpadflt and compute and output the average and standard average of the mean, using both linear and log averages.
colmerge.for	Merge entries in a series of single column files, such as those produced by BIPadFlt, into one single column file.
col_rat.for	Make a file with ratios of columns from specified column-formatted files.

smc2fasrat.for	Compute the ratio of Fourier amplitude spectra for specified time series. The program is unfinished; see the code for a work-around.
psv_avg.for	Read a column-oriented file made by blpadflt and compute and print out the average and standard average of the mean, using both linear and log averages.
rs2_asc.for	Read up to 72 response spectra written as SMC files and combine into a single column file; optionally will average two spectra and apply corrections to a common distance and V30 (not finished yet).
<b>Miscellaneous</b>	
smc_sort.for	Reads a list of SMC files made with the command “dir/on/b *.smc > smc.lst” and rewrites the list, sorting so that the uncorrected, acceleration, velocity, and displacement files are in order. Use in building a control file for smctsplt.
smcwinno.for	Extracts a subset of files from a list based on a specified character string in the file name. This program can be used in combination with a dos dir/on/b command to generate a list of file names to be used as input into programs for which only the subset is needed.
tabsexpnd.for	Read a list of files from a control file and replace tab characters with a specified number of spaces.
unix2pc.for	Reformats a unix ASCII file to a pc ASCII file
a09_a32.for	Reformats a unix ASCII file to a pc ASCII file by replacing ASCII character 09 with ASCII character 32 (blank).
add_cr.for	Adds an extra carriage return to each line, resulting in double spaced text when printed.
mac2pc.for	Reformats a Mac ASCII file to a pc ASCII file.

## Subroutines

The subroutines are listed alphabetically in the table below rather than by function or frequency of use. As noted previously, some of the programs are more widely used than others. For example, **smcread** and **smcwrite** are the main subroutines for reading and writing SMC files, and **fork** and **rdrvaa** are the main subroutines for computing Fourier Amplitude and response spectra, respectively. The subroutines **get\_lun** (to return the largest unused logical unit number), **trim\_c** (to remove leading and trailing blanks from a character string), **upstr** (to convert a string to uppercase), **skip** (to skip a specified number of lines when reading a file), and **skipcmnt** (skips over comment lines, which start with “!”, when reading a control file) are used in almost every main program (note that comments in SMC-formatted files are preceded by “[”, not “!”). **Smooth** is a useful subroutine that allows various smoothing operators. **Filter** calls the time-domain filtering programs.



The subprograms taken from Numerical Recipes (Press et al., 1992) have been collected into a separate table, as I am not allowed to distribute the source code for these subprograms. Information about obtaining the code can be found at <http://www.nr.com/>.

**Table 7.** Subroutines (except for those from Numerical Recipes).

<b>Subroutine Name</b>	<b>Subroutine Description</b>
abs_mnmaxidx.for	Return minimum and maximum values of an array, along with the indices of the array corresponding to these values.
absspect.for	Apply a tapered window to the front and back of a time series, pad with zeros to next power of 2, and compute the Fourier spectral amplitude.
absspect_complex.for	Apply a tapered window to the front and back of a time series, pad with zeros to next power of 2, and compute the complex Fourier spectrum.
acc2vd.for	Integrate acceleration to obtain velocity and displacement.
accsqint.for	Integrate the square of the acceleration (in order to compute Arias intensity).
ampphphd.for	Compute the amplitude, phase/ $2\pi$ , and if desired, the derivative of phase with respect to angular frequency.
band.for	Bandpass time-domain Butterworth filter (can be causal or acausal).
bjf94v30amp.for	Compute site amplifications using Boore et al. (1994) results.
bjf97.for	Return ground-motion values from the Boore et al. (1997) ground-motion prediction equations (GMPEs).
blpadflt_util_subs.for	This collection of subroutines available individually in this table is used by blpadflt.for.
byte_swap.f90	Used in sac2smc (written by C. Stephens).
cann.for	A character string subroutine from C. Mueller.
cav_compute.for	Compute the cumulative absolute velocity (CAV)
cmplxspc.for	Apply a tapered window to the front and back of the time series, pad with zeros to next power of 2, and compute the complex Fourier spectrum.
conditn.for	Apply a tapered window to the front and back of the time series and pad with zeros to

	the next power of two if needed.
construct_filename_extension.for	Constructs a character string containing information about the blpadflt option and filtering parameters. This subroutine is used in filt_plot to construct the names of the time series that are plotted.
correl_dmb.for	Compute correlation between two time series (used in smccorrl.for).
csr123.for	Parse next field in a comma-separated character string (from C. Mueller).
csrc.for	Extract a character string from a larger comma-separated string (from C. Mueller).
csrf.for	Extract a real number from a character comma-separated string (from C. Mueller).
csri.for	Extract an integer from a character comma-separated string (from C. Mueller).
d2va.for	Compute velocity and acceleration from displacement, assuming the reverse of the formulas in acc2vd (which assumes straight-line segments between acceleration values).
datetime.for	Obtain date and time character strings using a system call.
dcdt.for	Fit mean or trend between indices indx1 and indx2, then remove mean or trend from whole trace.
deg2km_f.for	Convert lat, long into km north and east from a reference point.
digitize.for	Simulate analog-to-digital conversion, used in Boore (2003a).
dis2va_wang.for	Compute velocity and acceleration from displacement using finite difference operators. [adapted from G.-Q. Wang]
dist_3df.for	Compute various distance measures from a point on the Earth's surface to a rectangle with arbitrary orientation and location in space (used to obtain distance from a station to a finite fault).
dist3dmf.for	Call dist_3df for each of a number of rectangles and return the minimum distances.
distaz.for	Compute great circle distances between two points on the surface of a sphere.
downsample.for	Downsample a time series
downsample_wang.for	Downsample a time series (a modification of the routine downsample by G.-Q. Wang).

envelope.for	Compute the Hilbert tranform of y and use it to compute the envelope and instantaneous frequency.
evt2smc_subs.for	Various subroutines used by the evt2smc converter program
evt2smc_headers.txt	Statements brought into evt2smc via include statements.
fbctpr.for	Apply cosine tapers to the front and back ends of time series.
filter.for	Interface to filter subroutines band, locut, hicut.
fork.for	Compute complex-to-complex Fourier spectrum using FFT algorithm.
fs2read.for	Read Fourier spectrum from a file in FS2 format (a form of the SMC format for Fourier spectra).
fs2write.for	Write Fourier amplitude spectra into SMC format
get_abs_fas.for	Returns Fourier amplitude spectrum, smoothed and interpolated to specified frequencies, if desired.
get_avg.for	Compute the mean of array entries between two indices.
get_date.for	Calls the Fortran 90 internal routine DATE_AND_TIME and formats the date into a string “mm/dd/yyyy”.
get_lun.for	Get highest available logical unit number.
get_npw2.for	Find nearest power of two.
get_path_from_file_name.for	Extract path from a file name
get_path_from_system_call.for	Get path using a system call
get_time.for	Calls the Fortran 90 internal routine DATE_AND_TIME and formats the time into a string “hh:mm:ss.sss”.
getampph.for	Use a FFT to obtain the amplitude and phase spectrum.
getf_out.for	Construct output file name.
hicut.for	High-cut (low-pass) time-domain Butterworth filter (can be causal or acausal).
hilbert.for	Compute the Hilbert tranform of y and use it to compute the envelope and instantaneous frequency.
histfreq.for	Place data values into bins, to use in plotting a histogram.
imnmax.for	Find the minimum and maximum of an

	integer array.
indxlast.for	Find the last occurrence in string c_string of the single character c_char.
integrate_y.for	Compute cumulative integral of y assuming that y is represented by straight lines connecting the digitized values.
intrp_ts.for	Linearly interpolate unevenly t_in, y_in to evenly sampled time series with sps samples per second.
len_trim.for	Return length of TEXT without trailing blanks.
lin_interp.for	Compute linearly interpolated value of y.
locut.for	Low-cut (high-pass) time-domain Butterworth filter (can be causal or acausal).
mak_stem.for	Construct a stem name (stem) by appending up to 4 characters of tag with a 4-character string giving the period T.
mnmax.for	Find the minimum and maximum of a real array.
mnmaxidx.for	Find the minimum and maximum of a real array, along with the array index of the minimum and maximum.
mnmxixdp.for	mnmaxidx for a double precision array.
momntdmb.for	Subroutine moment, modified to compute the moment for array entries between specified indices.
newmnmax.for	Same functionailty as mnmaxidx.
notch.for	Notch time-domain Butterworth filter (can be causal or acausal).
notnumrc.for	Check character string to see if it has any non-numeric characters.
putspace.for	Used in sac2smc (written by K. Assatourians).
rc_subs.for	Contains include statements for RCC, RCF, and RCI
rcc.for	Extract a character string from a larger character string (from C. Mueller).
rcf.for	Extract a real number from a character string (from C. Mueller).
rci.for	Extract an integer from a character string (from C. Mueller).
rd_calc.for	Calculate relative displacement response spectrum.
rdcalcts.for	The same as rd_calc, but it also returns the time series of the oscillator response.

rdrvaa.for	Calculate relative displacement, relative velocity, and absolute acceleration response spectra.
readhdrs.for	Read headers of SMC and RS2 files.
rmv_crlf.for	Remove carriage return/line feed characters and replace with a blank.
rmv_mean.for	Determine mean from portion of time series "a" between t4mean_strt and t4mean_stop, and remove this mean from the whole time series.
rmvtrend.for	Remove a straightline fit to first and last points, replacing the input array with the detrended array.
rotate.for	Rotate z1, z2 into the azimuth azmr (stored in z1 on return) and azmr+90.
rs2rdhdr.for	Read headers of response spectra stored in rs2 format.
rs2read.for	Read response spectra stored in rs2 format.
rs2write.for	Write response spectra in SMC rs2 format.
skip.for	Skip a specified number of lines whe reading a file.
skipcmnt.for	Skip comments while reading a file.
smc_npts.for	Obtain length of time series stored in an SMC file.
smc_nsps.for	Obtain npts, sps of time series stored in an SMC file.
smcpadf.for	Pad a time series with leading and trailing zeros.
smcpadf_detrend.for	Pad a time series with leading and trailing zeros, with an option for removing a straight line fit to the first and last points.
smcread.for	Read SMC files.
smcwrite.for	Write SMC files.
smooth_interpolate.for	A general subroutine for smoothing the elements in an array. It is used by get_abs_fas.for, which in turn is called by smc2fs2.for. The smoothing can be over linear and log abscissa values. The subroutine can do smoothing or interpolation or both. The abscissa values at which the smoothed values are returned can be a different set than that corresponding to the input array. This subroutine includes the functionality of the individual smoothing operators in the "smooth" subroutines below.

smooth_konno.for	Smooth over log-spaced abscissa values, using Konno and Ohmachi weighting function (see BSSA 88, 228-241)
smooth_logbox.for	Non-weighted smoothing over log-spaced abscissa values.
smooth_logtriangle.for	Triangular-weighted smoothing over log-spaced abscissa values.
smooth_n.for	Smooth y over nsmooth points (an odd number!) using a triangular weighting function.
smths.for	Smooth amplitude spectrum with a triangle window (an old program, use smooth_n instead).
tab_xpnd.for	Replace tabs in a character string with a specified number of blanks.
tabl_a_6.txt	Table A-6 in Boore et al. (1997); used by bjf97.for.
tabs_rmv.for	Replace tabs in a character string with a blank.
time_diff.for	Returns the difference in time between two times obtained using get_time, which in turn calls the internal Fortran 90 routine DATE_AND_TIME. See the program listing for the proper use of DATE_AND_TIME.
timediff.for	Compute the time difference in seconds between times returned from two calls to the system clock. This subroutine used a character string for the time that was returned by an earlier version of get_time. For consistency with the new version of get_time (which uses a standard Fortran 90 intrinsic routine to obtain the system time), the subroutine time_diff.for should be used. Not all programs in this version of TSPP have been modified appropriately.
tpfrctn.for	Apply cosine tapers to beginning and end of an array.
trim_c.for	Remove leading and trailing blanks from a character string.
tsplot_sub.for	Includes the functionality of smctsplt.for, used in filt_plot.for to plot a unfiltered acceleration, zeroth-order-corrected velocity, and filtered displacements for a suite of filter corners on a single page.
unwrap.for	Attempt to unwrap the phase of a complex

	Fourier spectrum.
upstr.for	Convert a character string to upper case.
v2a.for	Compute acceleration from velocity, using the reverse process of going from acceleration to velocity.
v2ad.for	Compute acceleration and displacement from velocity.
wind_box.for	Apply weighting using a box window with leading and trailing cosine tapers.
yintrf.for	Linear interpolation (old, use lin_interp).
zeropad.for	Add zeros to end of time series; used when computing FFT (smcpadf is a more sophisticated version, used when filtering data).
zeropad2.for	Determine npw2 and add zeros to end of time series; used when computing FFT.

**Table 8.** Numerical Recipes subroutines.

<b>Subroutine Name</b>	<b>Subroutine Description</b>
dcovsrt.for	Numerical Recipes subroutine
dddply.for	Numerical Recipes subroutine
dfpoly.for	Numerical Recipes subroutine
dgaussj.for	Numerical Recipes subroutine
dlfit.for	Numerical Recipes subroutine
four1.for	Numerical Recipes subroutine
indexx.for	Numerical Recipes subroutine
interp.for	Numerical Recipes subroutine
locate.for	Numerical Recipes subroutine
moment.for	Numerical Recipes subroutine
select.for	Numerical Recipes subroutine
twofit.for	Numerical Recipes subroutine

## Sample Sessions

Many examples of processing are contained in the references below, and guidelines for usage are given in some of the control files. More examples illustrating the consequences of various processing parameters may be included in future versions of this report (additional examples are contained in some of my informal notes on a variety of topics—see [http://quake.wr.usgs.gov/~boore/daves\\_notes.php](http://quake.wr.usgs.gov/~boore/daves_notes.php). I plan on collecting some of these notes together and publishing them as a USGS Open-File report). I include here two sample sessions, containing results not included in the references below. The first sample session illustrates many of the processing steps, including formatting data from a data agency into SMC format, zoc processing, low-cut filtering (with and without tapers where the pads adjoin the data), and computation of Fourier and response spectra. The second session illustrates the results of different smoothing options in the computation of Fourier amplitude spectra.

### Session 1: Basic Processing

The records are from the 21 November 2004, 13:37 UTC, **M** 5.3 earthquake recorded on the island of Guadalupe (Jousset and Douglas, 2007). Here are some processing steps used in analyzing these data.

I have set the comments in the control files shown below in italics, although the ASCII files for the control files in the distribution package are in plain text.

#### 1. Convert from European Strong-Motion Database Format to SMC Format

I used program **esmd2smc** to do the conversion; here is the control file:

```
Control file for ESMD2SMC           ! first line
Name of summary file:
  esmd2smc.sum
Spc?
  N
Xfactr
  100.0
Input file name ("stop" in any column to quit):
501053xa.raw
501053za.raw
STOP
```

(I actually converted the format of many more time series in one run of **esmd2smc**; to simplify this example, I show only the two horizontal components of record 501053 being processed.)

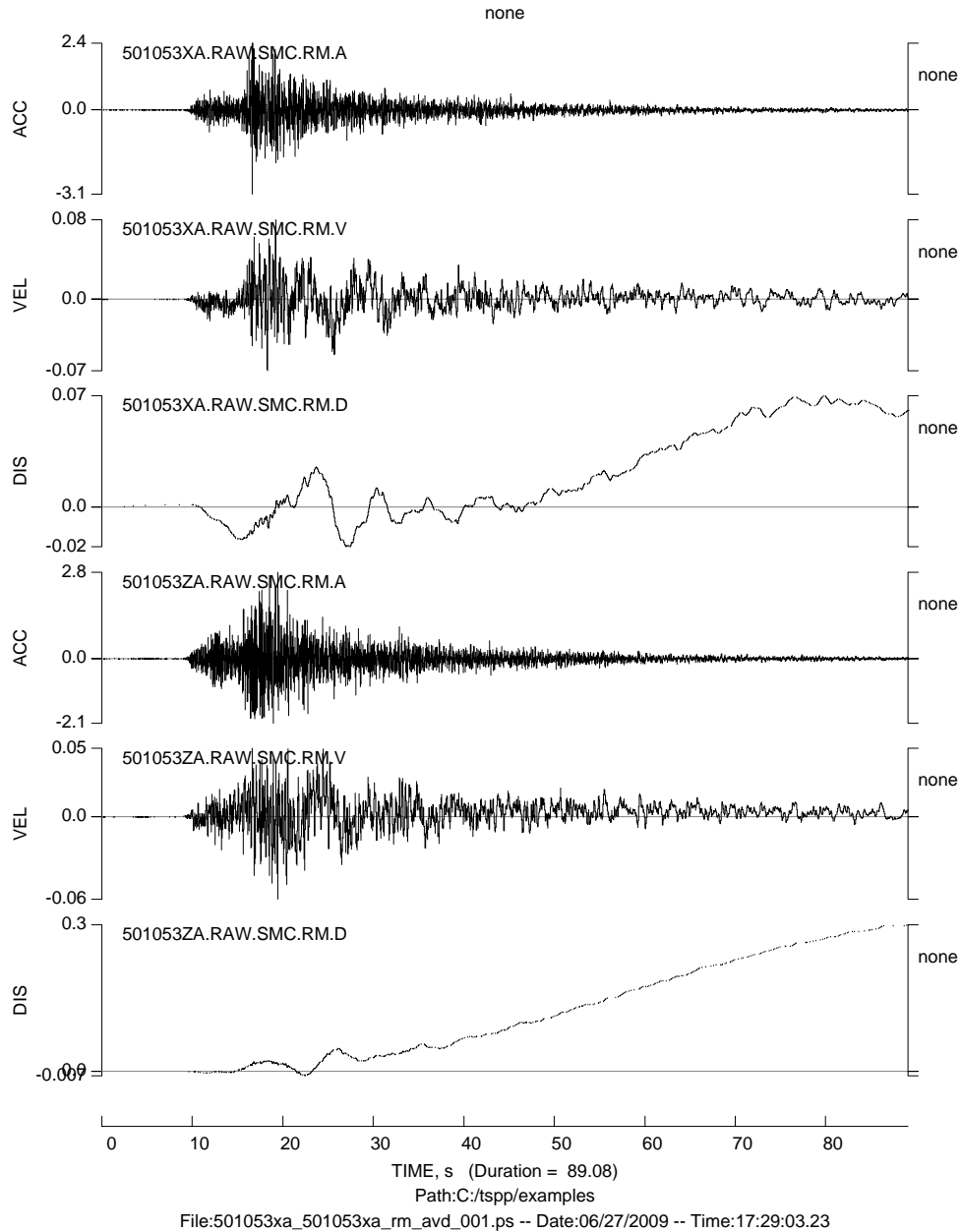
#### 2. Plot the Time Series

I then used **smctspl** to plot the time series in order to preview how much pre-event motion was available, and to check for obvious problems with the data.



### 3. Do ZOC (Zero-Order-Corrected) Processing

Using the plot made in Step 2, I chose the time range of 0 to 8 s for determining the mean to be removed from the whole record. I used **blpadfit** to do what I call the zoc or zero-order-corrected processing, and I used **smctsplit** to make plots of the resulting acceleration, velocity and displacement time series. Here is the plot:



**Figure 1.** Plot of acceleration, velocity, and displacement time series from zoc processing. Note that the grainy appearance is a result of the time series values being replaced by an average value per pixel, thus greatly speeding up the plotting and reducing the file size.

Note that the plot above is an Encapsulated PostScript (EPS) file, although the output of **smcstplt** is a PostScript (PS) file. I used **GSView** (<http://pages.cs.wisc.edu/~ghost/gsview/index.htm>) to make the conversion from PS to EPS.

#### 4. Filter, Integrate, Compute Response Spectra

The two horizontal components (components x and z in the plots below) were each processed with acausal, low-cut filters for two different frequency corners, one at 0.02 Hz and the other at 0.04 Hz (selected in part by visual inspection of the plot of the zoc velocity). In all cases the filter order is such that the filter decays as  $f^{-8}$  at low frequencies, and tapers of 0.0 and 20.0 s were applied at the start and end, respectively, of each record before adding zeros and filtering. All of the processing was done using **blpadflt**. The control file for the 0.02 Hz and 0.04 Hz filters with 20-s taper processing is shown here:

```
!Control file for program BLPadFlt
!
! Note on use of "!" to denote a comment line. This is only used
! for lines in the group of input lines containing processing
! parameters. Once "pp:" is encountered, the program assumes that
! all following lines until the next "pp:" or "stop" contain
! the names of files to be processed (note that this is consistent
! with file name restrictions: starting a file name with "!" is legal).
!
! Revision of program involving a change in the control file on this date:
! 02/15/09
!Summary file name:
! blpadflt.sum
!
! NOTE: Those parameters most likely to stay fixed are immediately below,
! before the list of files. Those likely to change for various groups
! of files are set below the "pp:" line.
!
!PARAMETERS FOR OBTAINING THE MEAN:
!
! mean info (contained after "pp:" line below):
! type of mean (0=no correction, 1=standard average; -1=specify mean)
! t4mean_strt, t4mean_stop, mean (use if type = -1)
! NOTE: need entries even if the parameter is not used (because read
! info use list-directed [unformatted] input)
!
!PARAMETER FOR DETRENDING AFTER MEAN REMOVAL STEP:
!
! 0 = NO; 1 = YES (the detrending removes a straight line fit to the first
! and last points)
!
!PARAMETERS FOR BASELINE ADJUSTMENT:
!
! Info is after "pp:" line below; here are the meanings:
! -Option (0=specfy T1 & T2; 1=Iwan 1; 2=Iwan 2; 3=t1,t2 from velfit; 10= no bl)
! (option 4: remove pulse between T1 and T2, whose area equals the mean of
! the velocity from t2b to t2e)
```

```

! -Fit d or v (0, 1), norder (1:line;2:quad.;3:cubic, etc-- 11 max), prcntfrtpr
! -Array indicating which coefficients are fixed at 0 (0) or are free (1);
! there must be norder+1 values
! -Torigin, T1b, T1e, T2b, T2e: The equation fitted to the velocity or
! displacement is relative to an origin at t = Torigin. For example,
! a straightline fit to velocity will have the equation
!  $v = c(1) + c(2)*(t-torigin)$ . The Torigin option was included to allow for
! a baseline correction starting at t1=t2=torigin,
! in particular when the polynomial is constrained to be 0.0 at t=torigin
! (this is specified by setting the first element in the array of coefficients
! in the preceding line to 0.0). The coefficients of the fitted polynomial
! are chosen so as to minimize the sum of the squared residuals between
! T1b--T1e and T2b--T2e. The first range (T1b--T1e) was included following
! the suggestion of V. Graizer to allow a portion near the beginning of the
! record to have some influence on the fitted function; in practice, this
! option is rarely used, and the usual specification is T1b = T1e = 0.0.
!
!PARAMETERS FOR ZERO PADDING:
!
! Add pads if apply acausal filter (Y/N)? This should almost always be
! set to "Y". Even if it is set to "N", note that the subroutine that
! does the filtering adds pads (but it does not go to the first zero crossing
! and it does not save the padded time series)
Y
! Factor by which the number of zeros is increased beyond that determined by
! the standard (BAP) equation.
1.0
! Replace discarded portions of original data with zeros (Y/N)? By doing this,
! two horizontal components with the same number of time points before
! padding (the usual case) will have the same number after padding and can
! be rotated.
Y
!
! Go to first zero crossing?
Y
! Use first point if smaller than first zero crossing?
Y
! Go to last zero crossing?
Y
! Use last point if smaller than last zero crossing?
Y
!
! IMPORTANT NOTE: Care must be taken if the zero pads start at a point
! determined by going inward to the first or last zero crossings
! ("Go to first/last zero crossing = T"). Look at the headers of the smc files
! to see how many data points were skipped.
! Sometimes the beginning or end of the unfiltered time series has a drift, in
! which case too many points will be skipped before the first zero crossing is
! reached.
!
! 11/03/06 - If zcross_l or zcross_t = F and use_first or use_last = T,
! pad with values equal to the last points. Allow this option
! to deal with cases such as filtering a displacement
! time series with a low-frequency drift, which will have
! a step offset if pad with zeros at the end. Be careful in
! in using this option for the first points, however (in
! a future version I may eliminate the option for the beginning,

```

```

!           as generally the leading pad should be zero). The need for
!           this option arose when I tried to filter a displacement
!           obtained by integrating a zeroth-order corrected acceleration.
!           The results were different than filtering the acceleration
!           before integration.
!           IF WANT TO PAD WITH ZEROS, STARTING AT
!           BEGINNING AND END OF DATA, SET ZCROSS_L, ZCROSS_T = F AND
!           USE_FIRST, USE_LAST = F (This is potentially confusing, and
!           I may remove the option of padding with the first and last
!           values in a later version of the program)
!
! Remove mean before determining segment to be padded?
! If Yes, the mean will be determined from the whole record. If this
! is not desireable, remove the mean outside of this program
N
! Remove mean after determining segment to be padded (the segment
! will probably be different than the segment originally used to determine the
! mean, and therefore the mean will no longer be 0.0. But then after removing
! this mean, the segment to be padded will not be at 0.0 values, but I
! hope this is a small problem. I probably should iterate):
N
! Save padded time series? (".pad" will be appended to file name)
Y
!
!PARAMETERS FOR FILTERING:
!
! flc, nslope_lc, fhc (0 = no filter), nslope_hc, icaus(1=causal)
! (nslope >= 2,4,6, etc for causal and 4,8,12, etc for acausal; this is
! enforced in the program)
! note that nslope is the asymptotic power of frequency, so that the filter
! goes as  $f^{\{nslope\}}$  for a low-cut filter and  $f^{\{-nslope\}}$  for a
! high-cut filter. In previous versions I used "nroll" as the parameter
! controlling the asymptotic behavior of the filter, the reason being that it
! is the parameter used by the filter routines in BAP. This was always
! confusing, so I switched to nslope on 27 Oct. 2005, with a translation to
! nroll in blpadflt (nroll = 0.5*nslope for causal and
! nroll = 0.25*nslope for acausal). (Note more confusing terminology:
! nroll = 0.5*npoles for a causal Butterworth filter.)
! The response of an acausal filter
! is not that of a Butterworth, because time domain filters are used.
! Bazzuro et al. (2004 COSMOS paper) use the terminology npnp, where
! "n" is the number of poles of a standard Butterworth filter. The "npnp"
! notation is used to indicate that two passes of a Butterworth filter are
! used. So, for example, "2p2p" means that two passes of a two-pole
! Butterworth filter are used, with an asymptotic dependence as  $f^4$  (for a
! low-cut filter). This notation is used to distinguish this case
! from that in which an acausal filter is simulated in the frequency domain, in
! which case the filter can have a true Butterworth response function. For that
! case, a "4p" acausal filter constructed in the frequency
! domain and using the standard Butterworth response would have the same
! asymptotic dependence ( $f^4$ ).
!
!PARAMETERS FOR RESPONSE SPECTRA:
!
!Periods for response spectra (nperiods log spaced from per_low to per_high):
200 0.01 90
!Damping values (ndamp, damp(1), damp(2), ..., damp(ndamp)):

```

```

1 0.05 0.20
!
!PROCESSING PARAMETERS AND FILES, IN GROUPS
!
pp: new set of parameters
!mean: type (-1=specify,0=none,1=standard), t4mean_strt, t4mean_stop,
!mean (use if type = -1):
1 0.0 8.0 -999.
!detrend after mean removal (0=no, 1=yes, in which case a line fit to
!the first and last points is removed; note that the mean need not be removed
!before detrending if type = 0 above):
0
!Option (0=spcfy T1 & T2; 1=Iwan 1; 2=Iwan 2; 3=t1,t2 from velfit; 4=pulse;
! 10= no bl)
10
!T1,T2 (options 0,4;A1,A2 if <0);A1,A2 (option 1); T1 (option 2; A1 if T1<0.0):
10.0 20.0
!Fit d or v (0, 1), norder (1:line;2:quad.;3:cubic, etc-- 11 max), prcntfrtpr:
1 3 0
!Array showing coefficients fixed at 0 (0) or free (1); must be norder+1
!values:
0 0 1 1 ! cubic, with first and second terms constrained to zero
!Torigin, T1b, T1e, T2b, T2e (fit between T1b--T1e and T2b--T2e):
0.0 0.0 0.0 56.0 200.0
! flc, nslope_lc, fhc (0 = no filter), nslope_hc, icaus(1=causal) (nslope >= 2)
! (nslope >= 2,4,6, etc for causal and 4,8,12, etc for acausal; this is
! enforced in the program)
0.02 8 0.0 4 0
!Length of taper at beginning and end of time series, before adding zeros
! (Not used if no filter or a causal filter, but still need this parameter
! (in the input file):
0.0 20.0
!character string to append to filename to make the output filename:
! if this character string equals "<auto>", the extension will be constructed
! from the filter information (e.g., for a 0.125 Hz acausal low-cut filter
! with a slope of 8, the extension will be '.alc00.125ns08').
.alc0p02_taper_20s
!integrate to velocity and displacement? (y/n):
y
!Names of files to be processed with the parameters above:
501053xa.raw.smc
pp: new set of parameters
!mean: type (-1=specify,0=none,1=standard), t4mean_strt, t4mean_stop,
!mean (use if type = -1):
1 0.0 8.0 -999.
!detrend after mean removal (0=no, 1=yes, in which case a line fit to
!the first and last points is removed; note that the mean need not be removed
!before detrending if type = 0 above):
0
!Option (0=spcfy T1 & T2; 1=Iwan 1; 2=Iwan 2; 3=t1,t2 from velfit; 4=pulse;
! 10= no bl)
10
!T1,T2 (options 0,4;A1,A2 if <0);A1,A2 (option 1); T1 (option 2; A1 if T1<0.0):
10.0 20.0
!Fit d or v (0, 1), norder (1:line;2:quad.;3:cubic, etc-- 11 max), prcntfrtpr:
1 3 0
!Array showing coefficients fixed at 0 (0) or free (1); must be norder+1 values:

```

```

0 0 1 1 ! cubic, with first and second terms constrained to zero
!Torigin, T1b, T1e, T2b, T2e (fit between T1b--T1e and T2b--T2e):
0.0 0.0 0.0 56.0 200.0
! flc, nslope_lc, fhc (0 = no filter), nslope_hc, icaus(1=causal) (nslope >= 2)
! (nslope >= 2,4,6, etc for causal and 4,8,12, etc for acausal; this is
! enforced in the program)
0.04 8 0.0 4 0
!Length of taper at beginning and end of time series, before adding zeros
! (Not used if no filter or a causal filter, but still need this parameter
! (in the input file):
0.0 20.0
!character string to append to filename to make the output filename:
! if this character string equals "<auto>", the extension will be constructed
! from the filter information (e.g., for a 0.125 Hz acausal low-cut filter
! with a slope of 8, the extension will be '.alc00.125ns08').
.alc0p04_taper_20s
!integrate to velocity and displacement? (y/n):
y
!Names of files to be processed with the parameters above:
501053xa.raw.smc
stop

```

This control file produced the following files for the x-component and the 0.02 Hz filter (three other sets of files were also produced, one for the x-component filtered at 0.04 Hz, and two corresponding sets for the z component):

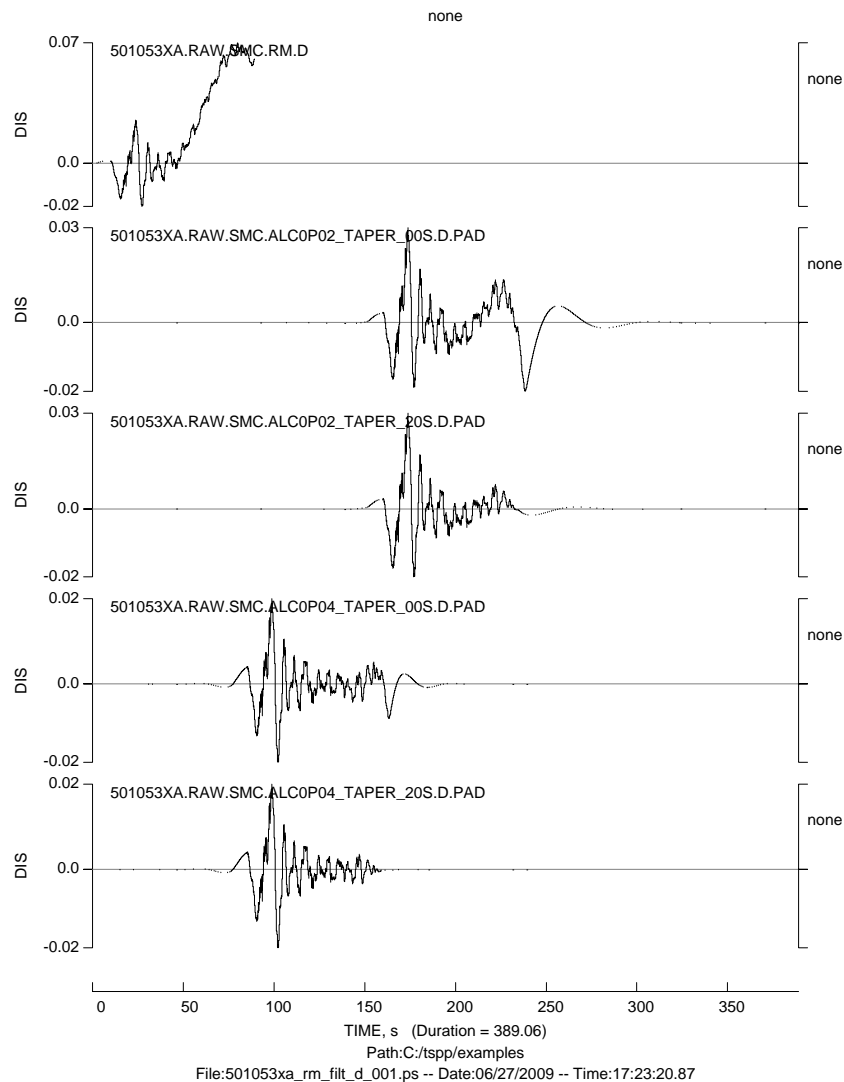
**Table 9.** Files produced by **blpadflt**, using the control file above.

File Name	File Description
501053xa.raw.smc.alc0p02_taper_20s.a	Pad-stripped acceleration for component x, 20 s taper, and 0.02 Hz filter.
501053xa.raw.smc.alc0p02_taper_20s.a.pad	Acceleration for component x, 20 s taper, and 0.02 Hz filter.
501053xa.raw.smc.alc0p02_taper_20s.v	Pad-stripped velocity for component x, 20 s taper, and 0.02 Hz filter.
501053xa.raw.smc.alc0p02_taper_20s.v.pad	Velocity for component x, 20 s taper, and 0.02 Hz filter.
501053xa.raw.smc.alc0p02_taper_20s.d	Pad-stripped displacement for component x, 20 s taper, and 0.02 Hz filter.
501053xa.raw.smc.alc0p02_taper_20s.d.pad	Displacement for component x, 20 s taper, and 0.02 Hz filter.

501053xa.raw.smc.alc0p02_taper_20s.r.col	Response spectrum (not in SMC format), with columns containing period, relative displacement, pseudo-relative velocity, pseudo-absolute acceleration, relative velocity, and absolute acceleration response spectra.
------------------------------------------	----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

## 5. Plot and analyze results

After filtering and integration using **blpadflt**, I used **smetsplt** to make plots of the displacements, which are shown below for the x-component:



**Figure 2.** Plot of displacement time series from zoc (top) and filtered processing. The 2<sup>nd</sup> and 3<sup>rd</sup> traces are for a 0.02 Hz acausal low-cut filter, with no taper and a taper of 20 s where the training zeros are added to the data; the bottom two traces show the same thing for a 0.04 Hz filter.

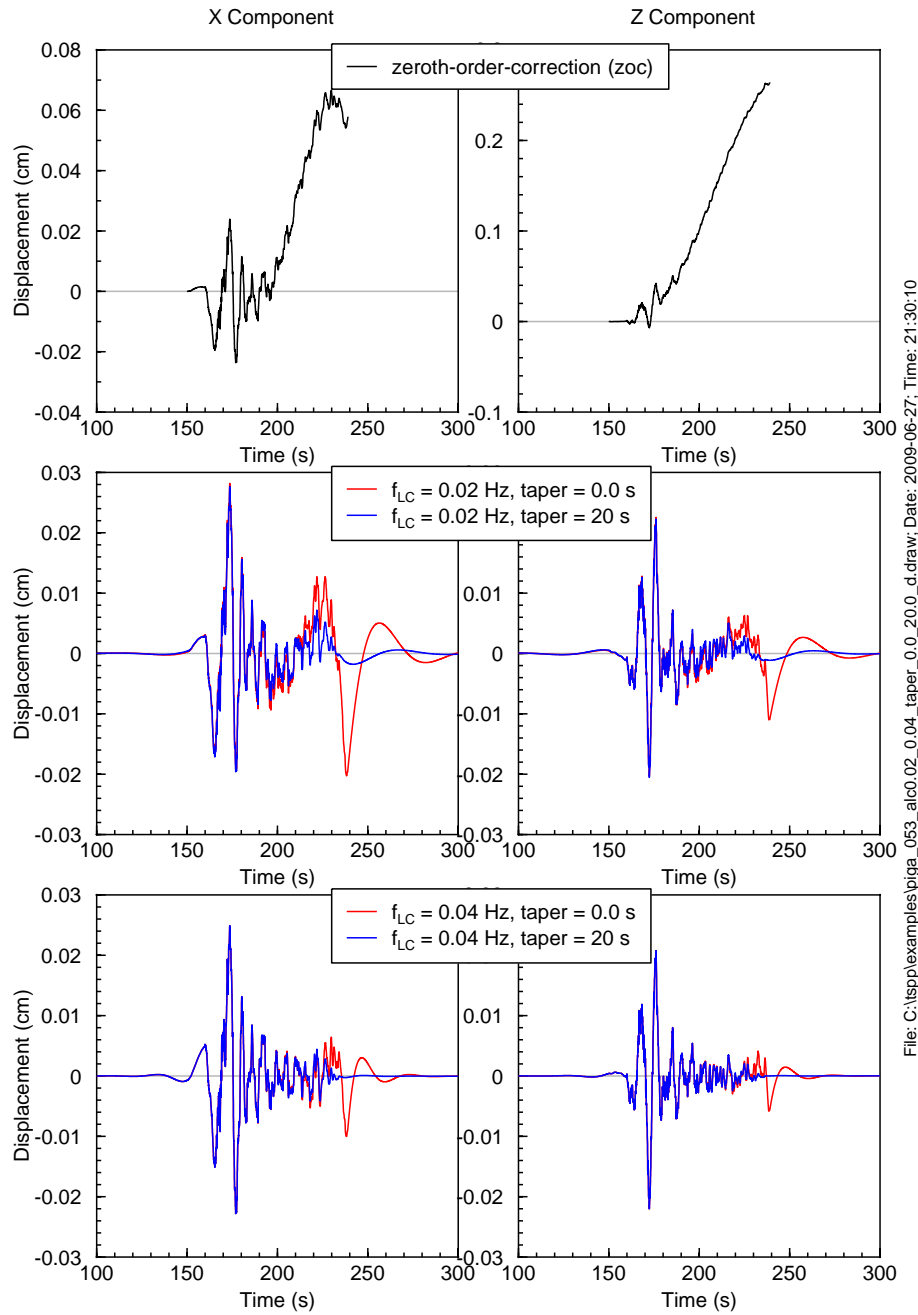
Also shown above are the results of using the 0.0 s taper (the z component is omitted for clarity). Note that the waveforms are shifted in time relative to one another because they are aligned by the first sample and not by the time of the first sample, which in each case varies according to the duration of the pre-signal pad that is applied.

Plots from **smc2spl**, like that above, are rough and intended to provide a quick overview of many time series on a single page. In order to make more precise plots of these particular time series I used **smc2asc** to merge the SMC files into a single column-oriented file, decimated the displacement time series by a factor of 5 (to save disk space and to generate smaller plot files; the original time series were sampled at 125 samples-per-sec (sps), and decimating by 5 leads to a sample rate of 25 sps, which is more than enough to display variations in the displacement waveforms) and time-shifted the displacements to allow the waveforms to line up; for each trace the shift was determined by using a text editor to look at the comments of the SMC files resulting from the **blpadflt** operation. Here is the **smc2asc** control file:

```
!Control file for SMC2ASC          ! first line
!Name of output file:
  501053_x_z_rm_0.02_0.04_taper_0_20_d.asc
!Want blank or 1e37 for blanks (1=blank)
  1
!Use first or last part of file name for column header (F, L)?
  F
! Processing parameters ndecim, skip, tlength, xfactr, tshift (+ to right)
! followed by the list for which these parameters will be used. The column
! labels will be made up of the file name (and no path)
! with "V" or "H" appended on the right to indicate component. The line
! with the processing parameters must have the string "pp:" somewhere before
! the parameters
!pp: 1  0.0 999.0 +1 0.0 ! ndecim, tskip, tlength, xfactr, tshift (+ to right)
!pp: 1 0.05 0.0 0 0.0 ! rs(0=RD,1=PSV,2=PSA,3=RV,4=AA), damp, placeholders(r,i,r)
!pp: 0 0.0 0.0 0 0.0 ! for Fourier spectra, use placeholders (i,r,r,i,r)
pp: 5  0.0 999.0 +1 149.992 ! ndecim, tskip, tlength, xfactr, tshift (+ to
right)
501053xa.raw.smc.rm.d
pp: 5  0.0 999.0 +1 0.0 ! ndecim, tskip, tlength, xfactr, tshift (+ to right)
501053xa.raw.smc.alc0p02_taper_00s.d.pad
501053xa.raw.smc.alc0p02_taper_20s.d.pad
pp: 5  0.0 999.0 +1 74.992 ! ndecim, tskip, tlength, xfactr, tshift (+ to right)
501053xa.raw.smc.alc0p04_taper_00s.d.pad
501053xa.raw.smc.alc0p04_taper_20s.d.pad
pp: 5  0.0 999.0 +1 149.992 ! ndecim, tskip, tlength, xfactr, tshift (+ to
right)
501053za.raw.smc.rm.d
pp: 5  0.0 999.0 +1 0.0 ! ndecim, tskip, tlength, xfactr, tshift (+ to right)
501053za.raw.smc.alc0p02_taper_00s.d.pad
501053za.raw.smc.alc0p02_taper_20s.d.pad
pp: 5  0.0 999.0 +1 74.992 ! ndecim, tskip, tlength, xfactr, tshift (+ to right)
501053za.raw.smc.alc0p04_taper_00s.d.pad
501053za.raw.smc.alc0p04_taper_20s.d.pad
stop
```



I then opened the output file in the graphics program CoPlot (<http://www.cohort.com/coplot.html>) and made the following plot:



**Figure 3.** Plot of displacement time series from zoc (top) and filtered processing, with and without tapers where the training zeros are added to the data.

The left and right columns show the results for the x- and the z-components, respectively. Note that the transient associated with adding trailing pads is worse for the x-component than for the z-component and is reduced for the higher-frequency filter. Using a taper reduces the size of the transient significantly.

Generating plots of displacement waveforms for various filters can help in the choice of the appropriate filter corner frequency, as shown in the Session 3 examples. This selection process can also be aided by plotting the Fourier amplitude spectra (FAS) of the acceleration traces. For the traces being considered here I computed the FAS with **smc2fs2**, using the following control file:

```
!Control file for program SMC2FS2
! As many comment lines as desired, each starting with "!"
! The string "pp:" indicates a new set of processing parameters
! to be applied to the following smc files. The parameters are given on the
! following 4 lines.
! NOTE: Use prcntftrtaper with caution. I recommend 0.0 at first.
! I've been burned a few times
! in computing FAS for unusual time series (eg., with long zero pads) in
! which the FAS looked OK at first glance, but then I discovered that
! it did not have the proper asymptotic properties or did not compare
! properly with other FAS (in the zero pad case, for frequencies greater than
! the lowest frequencies, the FAS for an unpadded and a 200s padded time series
! were identical, but for a 600s pad, the FAS was noticeably smaller. I finally
! tracked down the reason to the use of a 0.05% front taper. For the long
! time series for the 600s pad, the taper reduced signal).
!
! Meaning of smoothing input parameters
!
! NO SMOOTHING
! itype = 0
! SMOOTHING OVER EQUALLY SPACED FREQUENCIES
! itype = 1: box weighting function
!   smooth_param = width of box weighting function (Hz)
! itype = 2: triangular weighting function
!   smooth_param = width of triangular weighting function (Hz)
! SMOOTHING OVER LOGARITHMICALLY SPACED FREQUENCIES
! itype = 3: box weighting function
!   smooth_param = xi, which is the fraction of a decade for the
!                   box weighting function
! itype = 4: triangular weighting function
!   smooth_param = xi, which is the fraction of a decade for the
!                   triangular weighting function
! itype = 5: Konno and Ohmachi weighting function (see BSSA 88, 228-241)
!   smooth_param = xi, which is the fraction of a decade spanned by the
!                   first zero crossings for the
!                   Konno and Ohmachi weighting function
!
! ipow = power of FAS to be smoothed (2 = smoothing energy spectrum)
!
! df_smooth: Note: need df_smooth for linearly-spaced smoothers,
! and generally it should be the df from the fft. The reason for
! including it as an input parameter is to "fool" the
! program to do smoothing over a specified number of points by
! setting df = 1 and smooth_param = number of points (including
```

```

! points with zero weight at ends; e.g., smooth_param = 5 will
! give a smoother with weights 0, 1/4, 2/4, 1/4, 0; smooth_param
! should be odd).
!
!Name of summary file:
    smc2fs2.sum
pp: new set of parameters
!tskip, tlength, prctnftrtaper, signnpw2(<0, backup for npw2, no zpad):
    0.0 2000.0 0.0 +1.0
!dc_remove?
    .false.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
    0 1 0.0 15.0
!interpolation: df_intrp(0=FFT freqs), f_intrp_low, f_intrp_high, log-
spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrp as the number of
frequencies
    0.0 0.0 50.0 0
!character string to append to filename:
    .fs
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced
frequencies
! because programs such as smc2asc have not been modified to deal with log-
spaced
! frequency.
    Y
!Files to process:
501053xa.raw.smc.rm.a
501053xa.raw.smc.alc0p02_taper_00s.a.pad
501053xa.raw.smc.alc0p02_taper_20s.a.pad
501053xa.raw.smc.alc0p04_taper_00s.a.pad
501053xa.raw.smc.alc0p04_taper_20s.a.pad
stop

```

I then used **smc2asc** with the following control file to produce a column-oriented file containing the Fourier spectra:

```

!Control file for program SMC2FS2
! As many comment lines as desired, each starting with "!"
! The string "pp:" indicates a new set of processing parameters
! to be applied to the following smc files. The parameters are given on the
! following 4 lines.
! NOTE: Use prctnftrtaper with caution. I recommend 0.0 at first.
! I've been burned a few times
! in computing FAS for unusual time series (eg., with long zero pads) in
! which the FAS looked OK at first glance, but then I discovered that
! it did not have the proper asymptotic properties or did not compare
! properly with other FAS (in the zero pad case, for frequencies greater than
! the lowest frequencies, the FAS for an unpadded and a 200s padded time series
! were identical, but for a 600s pad, the FAS was noticeably smaller.
! I finally tracked down the reason to the use of a 0.05% front taper.
! For the long time series for the 600s pad, the taper reduced signal).
!
! Meaning of smoothing input parameters
!

```

```

! NO SMOOTHING
! itype = 0
! SMOOTHING OVER EQUALLY SPACED FREQUENCIES
! itype = 1: box weighting function
!   smooth_param = width of box weighting function (Hz)
! itype = 2: triangular weighting function
!   smooth_param = width of triangular weighting function (Hz)
! SMOOTHING OVER LOGARITHMICALLY SPACED FREQUENCIES
! itype = 3: box weighting function
!   smooth_param = xi, which is the fraction of a decade for the
!                 box weighting function
! itype = 4: triangular weighting function
!   smooth_param = xi, which is the fraction of a decade for the
!                 triangular weighting function
! itype = 5: Konno and Ohmachi weighting function (see BSSA 88, 228-241)
!   smooth_param = xi, which is the fraction of a decade spanned by the
!                 first zero crossings for the
!                 Konno and Ohmachi weighting function (it is related to
!                 their smoothing parameter b by the equation
!                  $b = 2.0 \cdot \pi / \text{smooth\_param}$ , so b = 20, 30 and 40 correspond to
!                 smooth_parameter = 0.31, 0.21, and 0.16, respectively.
!                 I prefer smooth_parameter = 0.4, which corresponds to
!                 b = 16).
!
! ipow = power of FAS to be smoothed (2 = smoothing energy spectrum)
!
! df_smooth: Note: need df_smooth for linearly-spaced smoothers,
! and generally it should be the df from the fft. The reason for
! including it as an input parameter is to "fool" the
! program to do smoothing over a specified number of points by
! setting df = 1 and smooth_param = number of points (including
! points with zero weight at ends; e.g., smooth_param = 5 will
! give a smoother with weights 0, 1/4, 2/4, 1/4, 0; smooth_param
! should be odd).
!
!Name of summary file:
    smc2fs2.sum
pp: new set of parameters
!tskip, tlength, prctnfrtaper, signnpw2(<0, backup for npw2, no zpad):
    0.0 2000.0 0.0 +1.0
!dc_remove?
    .false.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
    0 1 0.0 15.0
!interpolation: df_intrap(0=FFT freqs), f_intrap_low, f_intrap_high,
!log-spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrap as the number
! of frequencies
    0.0 0.0 50.0 0
!character string to append to filename:
    .fs.smc
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced
! frequencies because programs such as smc2asc have not been modified
! to deal with log-spaced frequency.
    y
!Files to process:

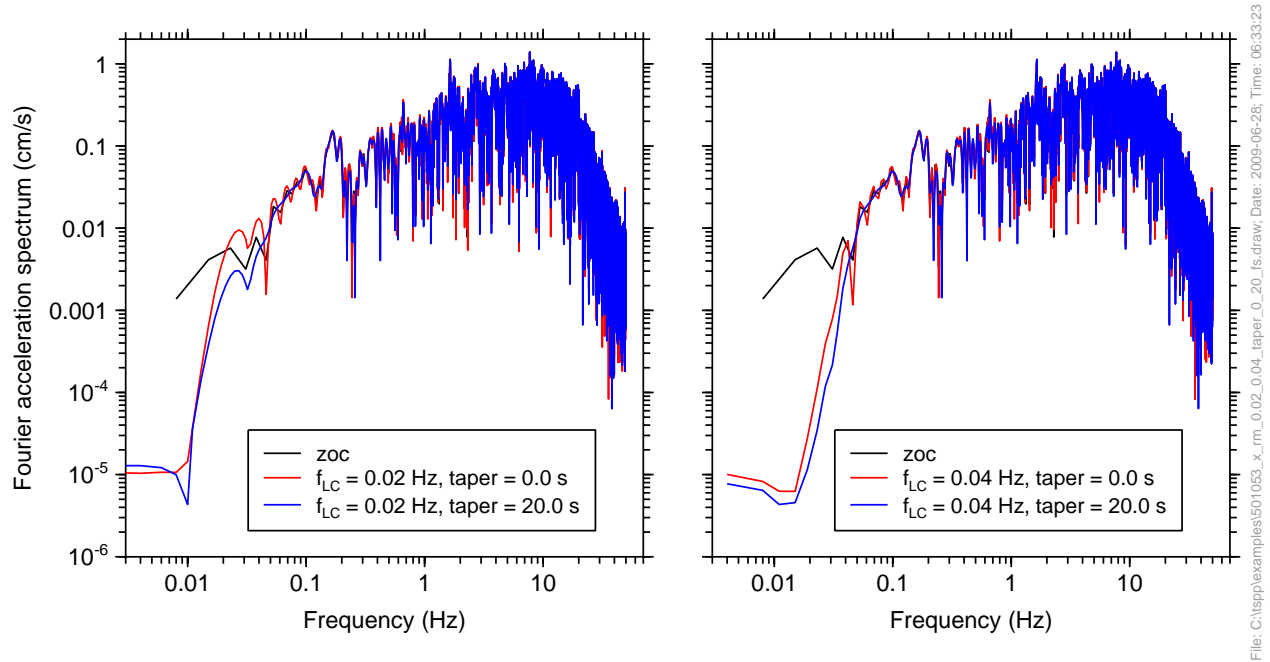
```

```

501053xa.raw.smc.rm.a
501053xa.raw.smc.alc0p02_taper_00s_padsx2.a.pad
501053xa.raw.smc.alc0p02_taper_00s_padsx2.a.pad
501053xa.raw.smc.alc0p02_taper_20s_padsx2.a.pad
501053xa.raw.smc.alc0p04_taper_00s_padsx2.a.pad
501053xa.raw.smc.alc0p04_taper_20s_padsx2.a.pad
stop

```

From the output of **smc2asc** the following plot was generated using CoPlot:



**Figure 4.** FAS of the acceleration time series corresponding to the processing used for the previous figures.

Although the choice of filter corner is subjective, I would choose a corner closer to 0.04 Hz than to 0.02 Hz, based on the decreasing slope with decreasing frequency starting around 0.03 Hz for the zoc FAS, and based on the general appearance of the displacement waveforms.

I also made plots of the relative displacement response spectra, using **colmerge** to combine the response spectral files made by **blpadflt**. Here is the control file for **colmerge**:

```

!Control file for program ColMerge
!Output file name:
501053_rm_alc0p02_0p04_taper_0.0_20.0_rs.col
!Use first or last part of file name for column header (F, L)?
L
!N lines to skip to get to data

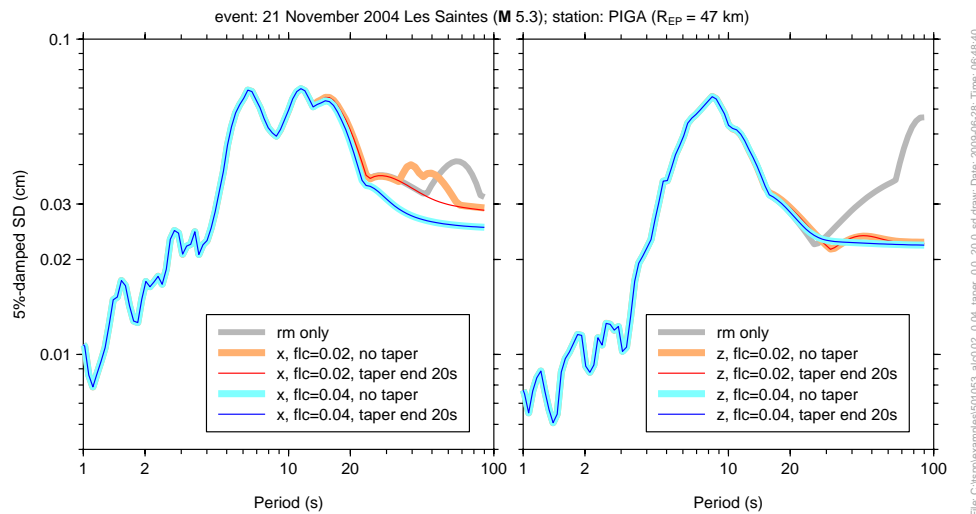
```

```

1
!N columns to read, columns for x and y columns
! (for files made using blpadflt, period is in column 1 and sd, pv, pa, rv,
! aa are in columns 2, 3, 4, 5, 6, respectively)
2 1 2
!Output a single x column? (y,n: if yes, use x column from first file):
n
!file ("STOP" in any column, any case, to quit)
501053xa.raw.smc.rm.r.col
501053xa.raw.smc.alc0p02_taper_00s.r.col
501053xa.raw.smc.alc0p02_taper_20s.r.col
501053xa.raw.smc.alc0p04_taper_00s.r.col
501053xa.raw.smc.alc0p04_taper_20s.r.col
501053za.raw.smc.rm.r.col
501053za.raw.smc.alc0p02_taper_00s.r.col
501053za.raw.smc.alc0p02_taper_20s.r.col
501053za.raw.smc.alc0p04_taper_00s.r.col
501053za.raw.smc.alc0p04_taper_20s.r.col
Stop

```

Here is the plot of the response spectra (starting at T=1 s to show more details at long periods, where the differences due to the various processing will appear):



**Figure 5.** Response spectra (SD) of the acceleration time series corresponding to the processing used for the previous figures.

Note that for the 0.04 Hz filter corner the response spectra for both tapers are indistinguishable, but this is not true for the 0.02 Hz filter and the x-component of motion (the time series plot above shows that the transient is particularly large for this case).

## Session 2: Smoothing Of FAS

This is an abbreviated session intended to illustrate some of the smoothing options in **smc2fs2**. In seismological applications Fourier amplitude spectra (FAS) are commonly plotted using a log scale for the frequency axis (and also for the ordinate axis). It is often desirable to work with a smoothed version of the FAS. FAS from FFTs are defined at equally spaced frequencies, and therefore smoothing using a weighting function that is symmetric when plotted using linear frequency may give what appears to be too much smoothing at low frequencies and not enough smoothing at high frequencies. There may be good technical reasons for choosing a smoothing convolutional operator whose width is constant in log-spaced or in linear-spaced frequency (e.g., Konno and Ohmachi, 1998, make such an argument), but I suspect that usually it comes down to subjective judgment: what looks best in the eye of the researcher. The type of smoothing should depend on why smoothing is being used in the first place. Consider the site response of a single uniform layer over a halfspace: the peaks and troughs are equally spaced in frequency, not log frequency, and in this case smoothing using a function with constant width in linear frequency may be appropriate. On the other hand, if the purpose of the smoothing is to reduce “noise” in a FAS that will be used to fit a spectral model, it might be more desirable to use a convolutional operator that has a constant width in log frequency.

The **smc2fs2** program allows five options for smoothing, two based on smoothing over a frequency-independent interval and three based on a smoothing operator whose width varies with frequency such that the width divided by the center frequency is constant (this corresponds to a constant width in log frequency). Box- and triangular-smoothing operators are available both for the frequency-independent and frequency-dependent smoothing operators. Another operator for the frequency-dependent case was proposed by Konno and Ohmachi (1998). Their operator uses the portion between the zero points on either side of the center frequency of a  $\sin \chi / \chi$  function as the smoothing operator---see their equation (4). Here is the relevant portion of the **smc2fs2** control files:

```
! Meaning of smoothing input parameters
!  

! NO SMOOTHING
! itype = 0
! SMOOTHING OVER EQUALLY SPACED FREQUENCIES
! itype = 1: box weighting function
!   smooth_param = width of box weighting function (Hz)
! itype = 2: triangular weighting function
!   smooth_param = width of triangular weighting function (Hz)
! SMOOTHING OVER LOGARITHMICALLY SPACED FREQUENCIES
! itype = 3: box weighting function
!   smooth_param = xi, which is the fraction of a decade for the
!                   box weighting function
! itype = 4: triangular weighting function
!   smooth_param = xi, which is the fraction of a decade for the
!                   triangular weighting function
! itype = 5: Konno and Ohmachi weighting function (see BSSA 88, 228-241)
!   smooth_param = xi, which is the fraction of a decade spanned by the
```

```

!           first zero crossings for the
!           Konno and Ohmachi weighting function (it is related to
!           their smoothing parameter b by the equation
!            $b = 2.0 \cdot \pi / \text{smooth\_param}$ , so b = 20, 30 and 40 correspond to
!           smooth_parameter = 0.31, 0.21, and 0.16, respectively.
!           I prefer smooth_parameter = 0.4, which corresponds to
!           b = 16).
!
! ipow = power of FAS to be smoothed (2 = smoothing energy spectrum)
!
! df_smooth: Note: need df_smooth for linearly-spaced smoothers,
! and generally it should be the df from the fft. The reason for
! including it as an input parameter is to "fool" the
! program to do smoothing over a specified number of points by
! setting df = 1 and smooth_param = number of points (including
! points with zero weight at ends; e.g., smooth_param = 5 will
! give a smoother with weights 0, 1/4, 2/4, 1/4, 0; smooth_param
! should be odd).
!

```

For smoothing using frequency-independent intervals, the smoothing parameter is the width of the smoothing operator. The program can be “fooled” to smooth over a specified number of points. The frequency spacing *df* is needed for the frequency-independent smoothing operators (usually given by the frequency spacing used in the FFT calculation), but by setting *df* = 1 and *smooth\_param* = number of points (including points with zero weight at ends; there should be an odd number of points), the smoothing will be done over the desired number of points. For example, *df* = 1 and *smooth\_param* = 5 will give a smoothing operator with weights of 0, 1/4, 2/4, 1/4, 0. For intervals that depend on frequency, the smoothing parameter is expressed as the fraction of a decade spanned by the operator (this is more understandable than the parameter used by Konno and Ohmachi).

I show in the figure below the results of smoothing using the frequency-independent triangular smoothing operator, using frequency intervals of 1, 2, and 4 Hz (the data are from the 08 January, 2006, M 6.7 Kythera, Greece, earthquake, recorded at station KRN1 at an epicentral distance of 146 km). The *smc2fs2* control file, deleting the comments portion shown above, for these three spectral computations is

```

pp: new set of parameters
!tskip, tlength, prctnfrtaper, signnpw2(<0, backup for npw2, no zpad):
    0.0 2000.0 0.0 +1.0
!dc_remove?
    .true.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
    2 1 0.0 1.0
!interpolation: df_intrap(0=FFT freqs), f_intrap_low, f_intrap_high,
!log-spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrap as the number
! of frequencies
    0.0 0.0 50.0 0
!character string to append to filename:
    .lintriangle_1.0.fs
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced

```

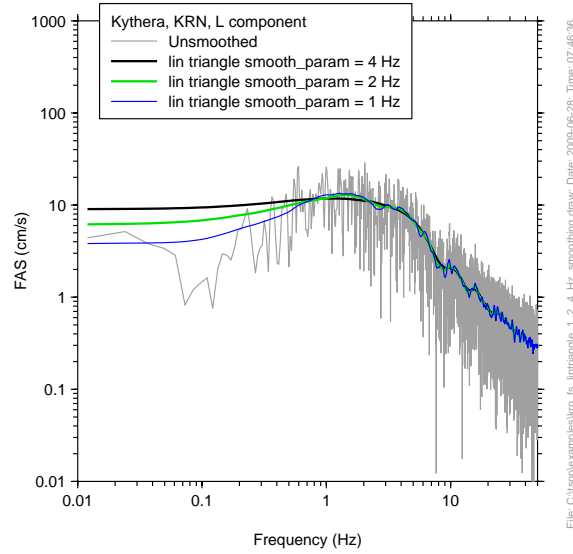


```

! frequencies because programs such as smc2asc have not been modified
! to deal with log-spaced frequency.
Y
!Files to process:
  krnl0601_1.smc
pp: new set of parameters
!tskip, tlength, prctnftrtaper, signnpw2(<0, backup for npw2, no zpad):
  0.0 2000.0 0.0 +1.0
!dc_remove?
  .true.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
  2 1 0.0 2.0
!interpolation: df_intrp(0=FFT freqs), f_intrp_low, f_intrp_high,
!log-spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrp as the number
! of frequencies
  0.0 0.0 50.0 0
!character string to append to filename:
  .lintriangle_2.0.fs
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced
! frequencies because programs such as smc2asc have not been modified
! to deal with log-spaced frequency.
Y
!Files to process:
  krnl0601_1.smc
pp: new set of parameters
!tskip, tlength, prctnftrtaper, signnpw2(<0, backup for npw2, no zpad):
  0.0 2000.0 0.0 +1.0
!dc_remove?
  .true.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
  2 1 0.0 4.0
!interpolation: df_intrp(0=FFT freqs), f_intrp_low, f_intrp_high,
!log-spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrp as the number
! of frequencies
  0.0 0.0 50.0 0
!character string to append to filename:
  .lintriangle_4.0.fs
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced
! frequencies because programs such as smc2asc have not been modified
! to deal with log-spaced frequency.
Y
!Files to process:
  krnl0601_1.smc
stop

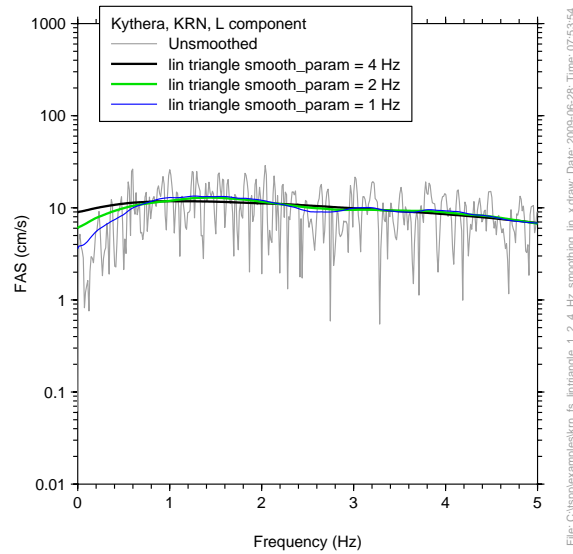
```

The program **smc2asc** was used to combine the output files into a single column-oriented file, and CoPlot was used to make the following plot:



**Figure 6.** FAS without smoothing and with frequency-independent triangular smoothing over frequency intervals of 1, 2, and 4 Hz.

Here is the same plot using linear scaling for the abscissa, and showing the frequency only to 5 Hz to allow more detail to be seen at low frequency:



**Figure 7.** FAS without smoothing and with frequency-independent triangular smoothing over frequency intervals of 1, 2, and 4 Hz, plotted using a linear frequency scale with a maximum frequency of 5 Hz.

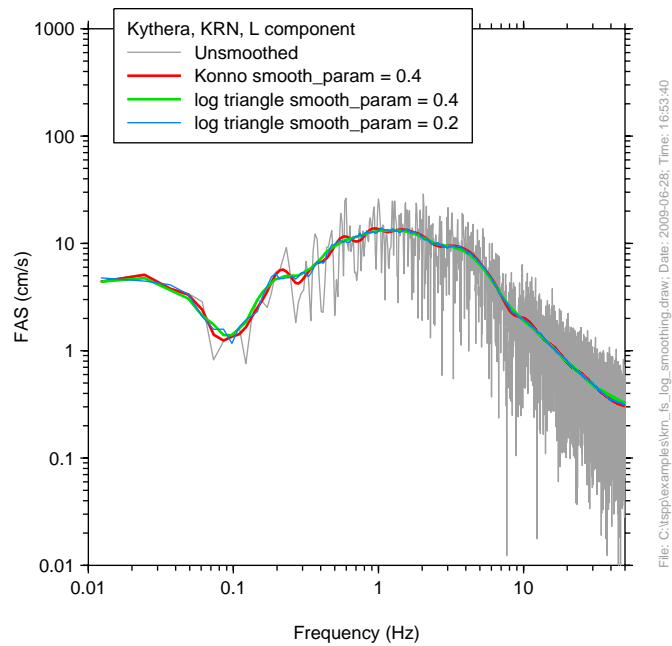
The excessive smoothing at low frequencies mentioned above is clearly seen in these plots. This excessive smoothing can be overcome by using one of the logarithmically spaced operators. The plots below show the results of three such operators, using the following control file:

```
pp: new set of parameters
!tskip, tlength, prctnfrtaper, signnpw2(<0, backup for npw2, no zpad):
    0.0 2000.0 0.0 +1.0
!dc_remove?
    .true.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
    3 1 0.0 0.2
!interpolation: df_intrap(0=FFT freqs), f_intrap_low, f_intrap_high,
!log-spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrap as the number
! of frequencies
    0.0 0.0 50.0 0
!character string to append to filename:
    .logbox_0.2.fs
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced
! frequencies because programs such as smc2asc have not been modified
! to deal with log-spaced frequency.
n
!Files to process:
    krnl0601_1.smc
pp: new set of parameters
!tskip, tlength, prctnfrtaper, signnpw2(<0, backup for npw2, no zpad):
    0.0 2000.0 0.0 +1.0
!dc_remove?
    .true.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
    4 1 0.0 0.4
!interpolation: df_intrap(0=FFT freqs), f_intrap_low, f_intrap_high,
!log-spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrap as the number
! of frequencies
    0.0 0.0 50.0 0
!character string to append to filename:
    .logtriangle_0.4.fs
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced
! frequencies because programs such as smc2asc have not been modified
! to deal with log-spaced frequency.
n
!Files to process:
    krnl0601_1.smc
pp: new set of parameters
!tskip, tlength, prctnfrtaper, signnpw2(<0, backup for npw2, no zpad):
    0.0 2000.0 0.0 +1.0
!dc_remove?
    .true.
!smoothing: itype, ipow, df_smooth (0 = FFT df), smooth_param:
    5 1 0.0 0.4
!interpolation: df_intrap(0=FFT freqs), f_intrap_low, f_intrap_high,
```

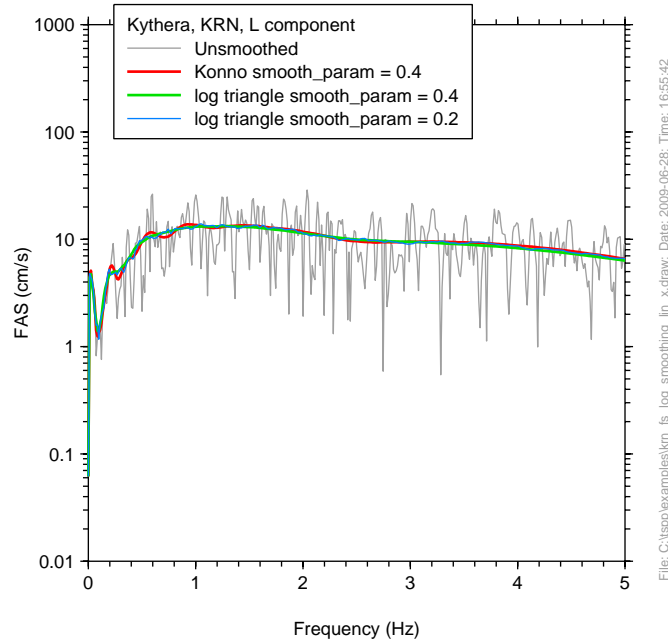
```

!log-spaced(0=F,1=T; integer)
! NOTE: if log-spaced_f = T, then interpret df_intrp as the number
! of frequencies
      0.0 0.0 50.0 0
!character string to append to filename:
      .konno_0.4.fs
!Output in smc format (Y,N)?
! ***IMPORTANT NOTE: Output cannot be in smc format if use log-spaced
! frequencies because programs such as smc2asc have not been modified
! to deal with log-spaced frequency.
      n
!Files to process:
      krn10601_1.smc
stop

```



**Figure 8.** FAS without smoothing and with frequency-dependent smoothing.



**Figure 9.** FAS without smoothing and with frequency-dependent smoothing, plotted using a linear frequency scale with a maximum frequency of 5 Hz.

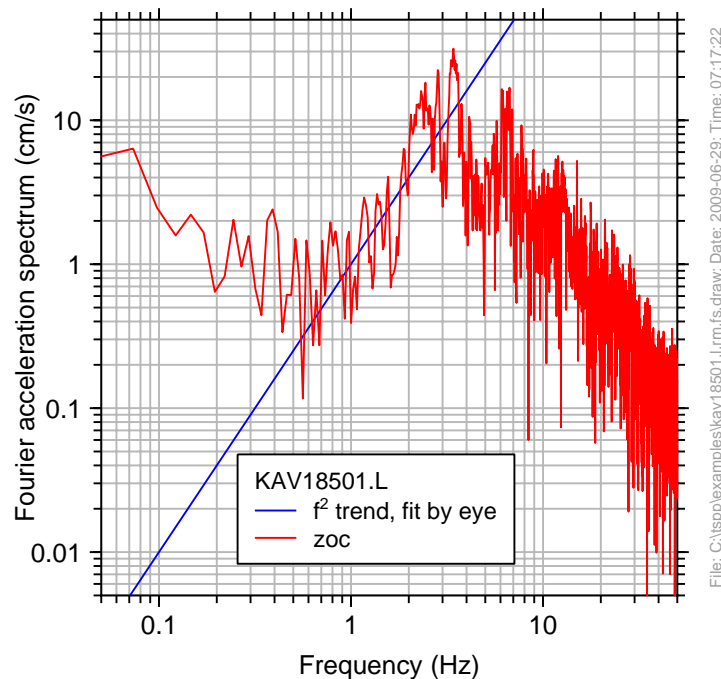
All of the smoothing operators work well at low frequency, but the box function has more chatter than the other two (use the zoom button in Acrobat to see this more clearly) and thus is the least desirable smoother (although in practical applications the difference between the three functions may not be important). The Konno and Ohmachi smoothing operator seems to be the preferable operator, although the program execution time is slower than the other operators because of the sine and log function evaluations; this is probably not relevant for most applications.

### Session 3: Runs to help in choosing the low-cut filter corner frequency

It is always a good idea initially to compute and graph the Fourier amplitude spectrum (FAS) and to compute unfiltered velocity and displacements from zero-order-corrected (zoc) acceleration data (acceleration data from which the mean of either the pre-event portion of the record, if available, or the complete record is removed from the whole record). Decisions about further processing, including the need for higher-order baseline corrections or filtering, should be based on both the FAS, and on a review of the zoc velocities and displacements for physical plausibility. Usually a low-cut filter is all the processing that is required. I show here two examples of choosing a low-cut filter. This section illustrates the use of the program *filt\_plot.for*, specifically written for use in deciding on the filter corner. The program does a series of filters with filter corners that are spaced equally in log frequency. The results (either velocity or displacement or both) are plotted on a single page, along with the original acceleration and the zoc velocity. Only two to four files are saved per run (counting the summary file and a file of response spectra, if requested), unlike *blpadflt*, which produces seven or eight files per run.

## A time series with a relatively simple Fourier acceleration spectrum

The first example used the record KAV18501.L.dat.smc. This was recorded at an epicentral distance of 45 km from an **M** 5.2 earthquake at 4 km depth in Greece; the earthquake occurred on 09 November 1985. Figure 10 shows the FAS for the uncorrected record.



**Figure 10.** FAS for the sample record. The blue line has a slope of 2, as expected from simple source theory; its location was determined by eye.

This is a fairly typical spectrum, with a decrease in amplitudes close to the theoretically expected slope of 2 (in a log-log plot) and an increase in amplitude at low frequencies, presumably due to noise. (What is unusual is the relatively high frequency at which the FAS starts to level out; simple source theory would have this starting near the corner frequency of the earthquake, which is about 1 Hz for a generic magnitude 5 earthquake.) Just based on the shape of the FAS, a filter corner near 1 Hz is suggested. To see the consequence of the filter frequency on the displacement waveforms, the program *filt\_plot.for* was used to make plots of the filtered displacements for a series of log-spaced frequencies ranging from 0.2 Hz to 2 Hz. The control file follows:

```
!Control file for program Filt_Plot
!
! Note on use of "!" to denote a comment line. This is only used
! for lines in the group of input lines containing processing
! parameters. Once "pp:" is encountered, the program assumes that
! all following lines until the next "pp:" or "stop" contain
```

```

! the names of files to be processed (note that this is consistent
! with file name restrictions: starting a file name with "!" is legal).
!
! Revision of program involving a change in the control file on this date:
    06/13/09
!Summary file name:
    filt_plot.sum
!
! NOTE: Those parameters most likely to stay fixed are immediately below,
! before the list of files. Those likely to change for various groups
! of files are set below the "pp:" line.
!
!PARAMETERS FOR OBTAINING THE MEAN:
!
! mean info (contained after "pp:" line below):
! type of mean (0=no correction, 1=standard average; -1=specify mean)
! t4mean_strt, t4mean_stop, mean (use if type = -1)
! NOTE: need entries even if the parameter is not used (because read
! info use list-directed [unformatted] input)
!
!PARAMETER FOR DETRENDING AFTER MEAN REMOVAL STEP:
!
! 0 = NO; 1 = YES (the detrending removes a straight line fit to the first and
last points)
!
!PARAMETERS FOR ZERO PADDING:
!
! Add pads if apply acausal filter (Y/N)? This should almost always be
! set to "Y". Even if it is set to "N", note that the subroutine that
! does the filtering adds pads (but it does not go to the first zero crossing
! and it does not save the padded time series)
Y
! Factor by which the number of zeros is increased beyond that determined by
! the standard (BAP) equation.
1.0
! Replace discarded portions of original data with zeros (Y/N)? By doing this,
! two horizontal components with the same number of time points before
! padding (the usual case) will have the same number after padding and can
! be rotated.
Y
!
! Go to first zero crossing?
Y
! Use first point if smaller than first zero crossing?
Y
! Go to last zero crossing?
Y
! Use last point if smaller than last zero crossing?
Y
!
! IMPORTANT NOTE: Care must be taken if the zero pads start at a point
! determined
! by going inward to the first or last zero crossings
! ("Go to first/last zero crossing = T").
! Look at the headers of the smc files to see how many data points were skipped.
! Sometimes the beginning or end of the unfiltered time series has a drift, in

```

```

! which case too many points will be skipped before the first zero crossing is
reached.
!
!      11/03/06 - If zcross_l or zcross_t = F and use_first or use_last = T,
!                  pad with values equal to the last points. Allow this option
!                  to deal with cases such as filtering a displacement
!                  time series with a low-frequency drift, which will have
!                  a step offset if pad with zeros at the end. Be careful in
!                  in using this option for the first points, however (in
!                  a future version I may eliminate the option for the
beginning,
!                  as generally the leading pad should be zero). The need for
!                  this option arose when I tried to filter a displacement
!                  obtained by integrating a zeroth-order corrected
acceleration.
!                  The results were different than filtering the acceleration
!                  before integration.
!                  IF WANT TO PAD WITH ZEROS, STARTING AT
!                  BEGINNING AND END OF DATA, SET ZCROSS_L, ZCROSS_T = F AND
!                  USE_FIRST, USE_LAST = F (This is potentially confusing, and
!                  I may remove the option of padding with the first and last
!                  values in a later version of the program)
!
! Remove mean before determining segment to be padded?
! If Yes, the mean will be determined from the whole record. If this
! is not desirable, remove the mean outside of this program
N
! Remove mean after determining segment to be padded (the segment
! will probably be different than the segment originally used to determine the
! mean, and therefore the mean will no longer be 0.0. But then after removing
! this mean, the segment to be padded will not be at 0.0 values, but I hope this
! is a small problem. I probably should iterate):
N
! Save padded time series? (".pad" will be appended to file name)
Y
!
!PARAMETERS FOR FILTERING:
!
! flc, nslope_lc, fhc (0 = no filter), nslope_hc, icaus(1=causal)
! (nslope >= 2,4,6, etc for causal and 4,8,12, etc for acausal; this is
! enforced in the program)
! note that nslope is the asymptotic power of frequency, so that the filter
! goes as  $f^{\{nslope\}}$  for a low-cut filter and  $f^{-\{nslope\}}$  for a high-cut filter.
! In previous versions I used "nroll" as the parameter controlling the
! asymptotic behavior of the filter, the reason being that it is the parameter
! used by the filter routines in BAP. This was always
! confusing, so I switched to nslope on 27 Oct. 2005, with a translation to
! nroll in blpadflt (nroll = 0.5*nslope for causal and
! nroll = 0.25*nslope for acausal). (Note more confusing terminology:
! nroll = 0.5*npoles for a causal Butterworth filter.)
! The response of an acausal filter
! is not that of a Butterworth, because time domain filters are used.
! Bazzuro et al. (2004 COSMOS paper) use the terminology npnp, where
! "n" is the number of poles of a standard Butterworth filter. The "npnp"
! notation is used to indicate that two passes of a Butterworth filter are
! used. So, for example, "2p2p" means that two passes of a two-pole
! Butterworth filter are used, with an asymptotic dependence as  $f^4$  (for a

```

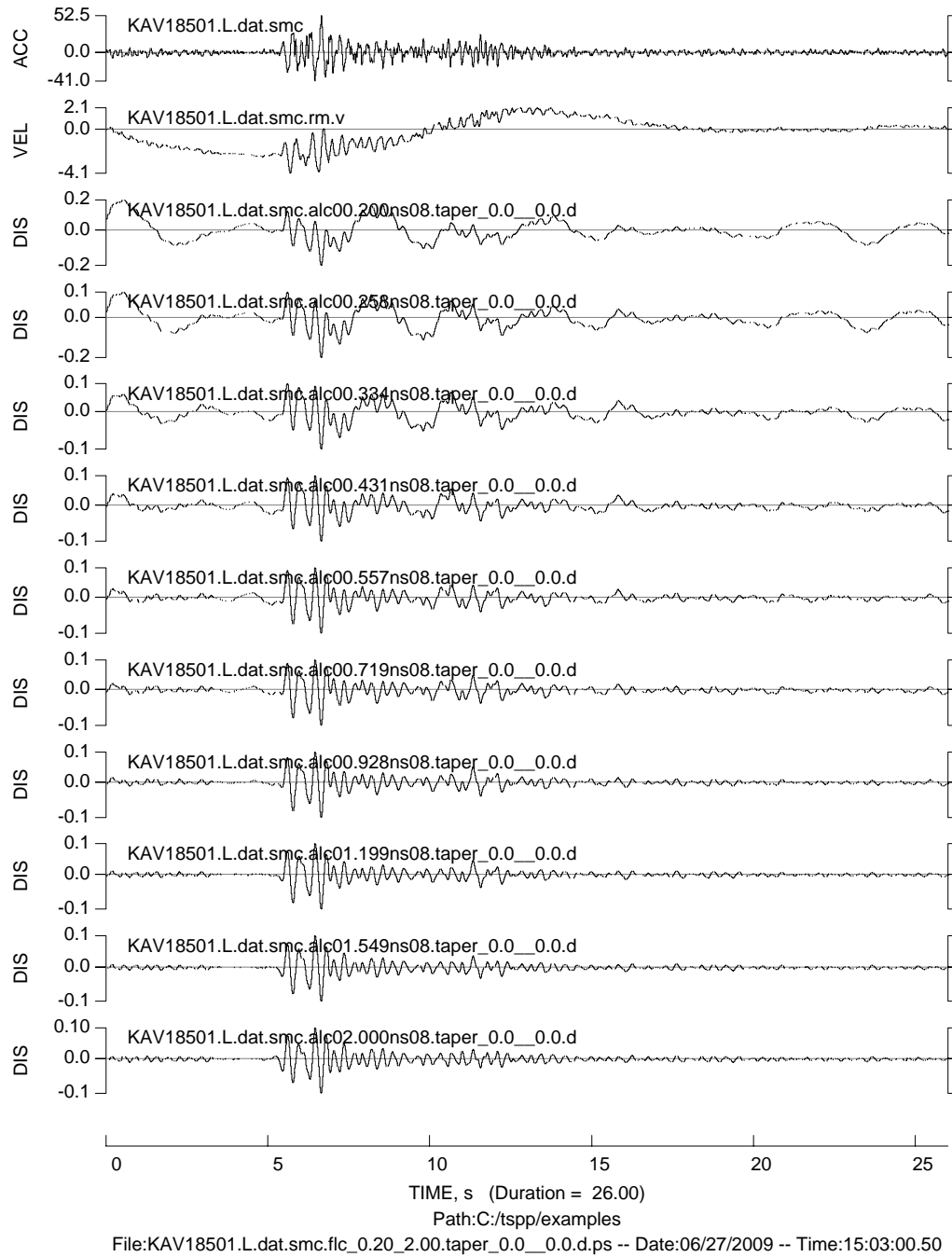


```

! low-cut filter). This notation is used to distinguish this case
! from that in which an acausal filter is simulated in the frequency domain, in
! which case the filter can have a true Butterworth response function. For that
! case, a "4p" acausal filter constructed in the frequency
! domain and using the standard Butterworth response would have the same
! asymptotic dependence ( $f^4$ ).
!
!RESPONSE SPECTRA PARAMETERS
!Periods for response spectra (nperiods log spaced from per_low to per_high):
  200 0.01 90
!Damping value
  0.05
!PLOT PARAMETERS
!Plot v(1), d(2), or both(3)?
  2
!start time, duration to plot (<=0 to start at 1st pt; >= 0 to plot all):
0.0 900.0
!peak-to-peak distance (cm) (ntraces*(p2p+0.5)<= 23.5, prog will reset if
needed)
  5.0
!PROCESSING PARAMETERS AND FILES, IN GROUPS
!
pp: new set of parameters
!mean: type (-1=specify,0=none,1=standard), t4mean_strt, t4mean_stop,
!mean (use if type = -1):
  1 0.0 2000.0 -999.
!detrend after mean removal (0=no, 1=yes, in which case a line fit to
!the first and last points is removed; note that the mean need not be removed
!before detrending if type = 0 above):
  0
!flow, fhigh, number of filters (<=10) (frequencies will be evenly spaced in log
f)
  0.2, 2.0, 10
!nslope_lc, fhc (0 = no filter), nslope_hc, icaus(1=causal) (nslope >= 2)
! (nslope >= 2,4,6, etc for causal and 4,8,12, etc for acausal; this is
! enforced in the program). These are the same for each flc
  8 0.0 4 0
!Length of taper at beginning and end of time series, before adding zeros
! (Not used if no filter or a causal filter, but still need this parameter
! (in the input file):
  0.0 0.0
!Names of files to be processed with the parameters above:
KAV18501.L.dat.smc
Stop

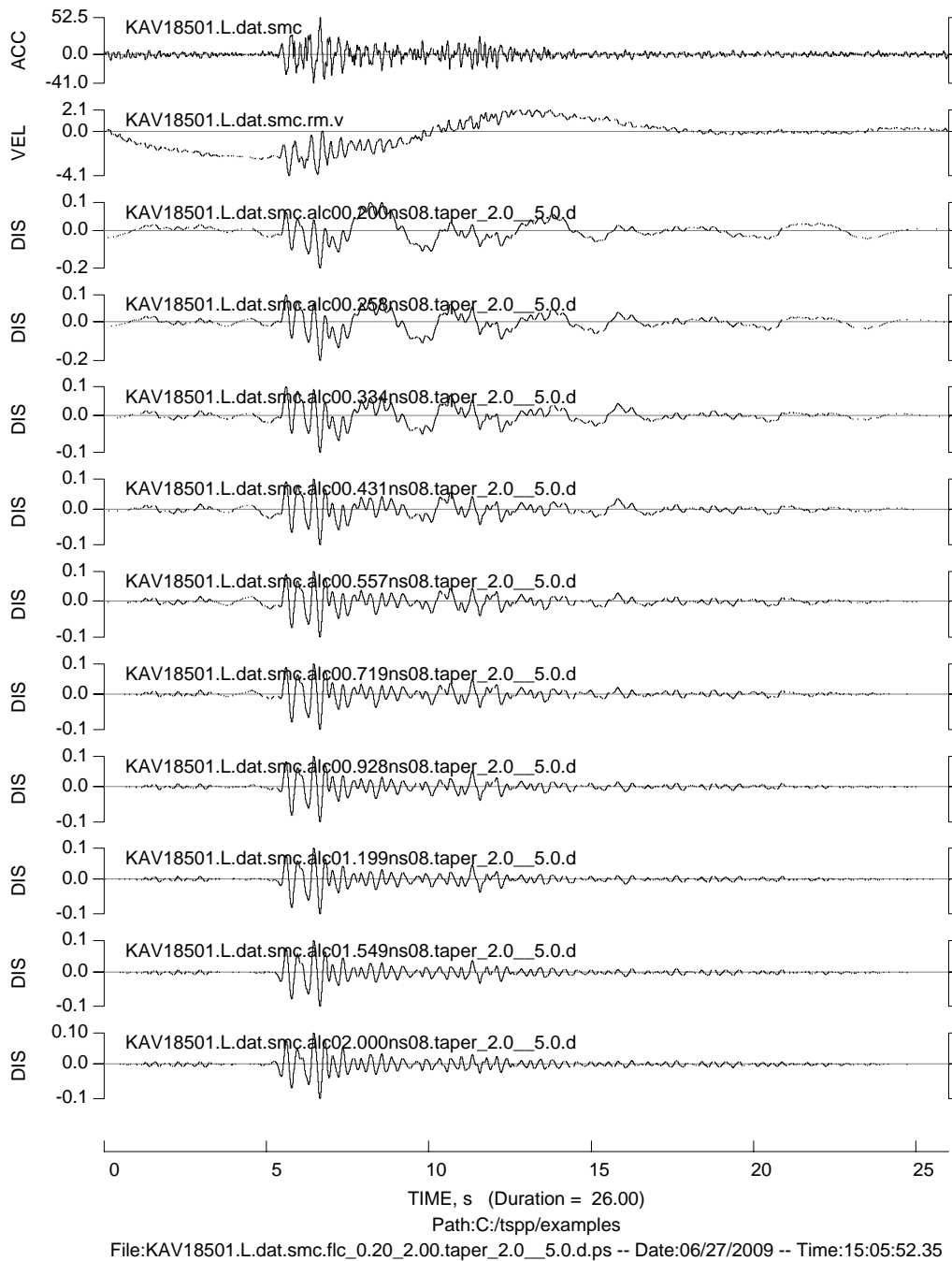
```

The program can create figures of the suite of filtered velocities, displacements, or both. In addition, it can compute response spectra for each filter and write to an output file. The control file above specifies that only displacements are plotted, and that 5%-damped response spectra are computed for 200 periods from 0.01 s to 90 s. The program produced the following plot:



**Figure 11.** A suite of displacements from filtered accelerations. The filter frequencies are part of the time series name above each trace (e.g., “alc00.431ns08” indicates that an acausal low-cut filter with corner frequency of 0.431 Hz and an order such that the filter goes as  $f^8$  at low frequencies was used). For ease of comparison, only pad-stripped time series are shown.

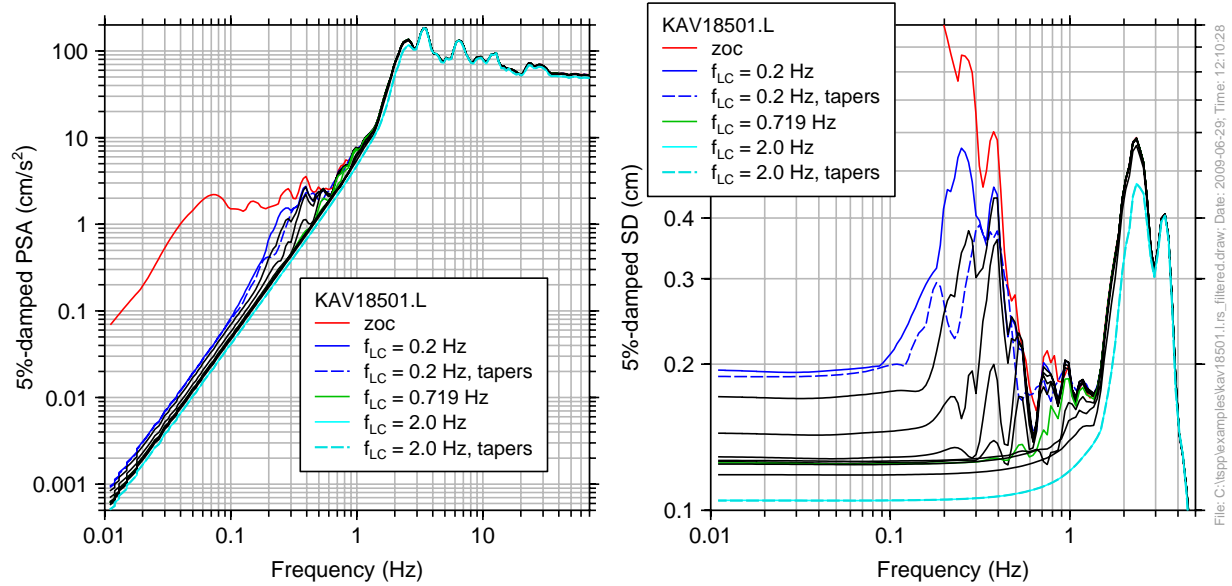
The small transients at the beginning and end of the time series (particularly evident for the lower-frequency filters) can be reduced by applying tapers, as shown in Figure 12.



**Figure 12.** A suite of displacements from filtered accelerations. The filter frequencies are part of the time series name above each trace (e.g., “alc00.431ns08” indicates that an acausal low-cut filter with corner frequency of 0.431 Hz and an order such that the filter goes as  $f^8$  at low frequencies was used). Tapers of 2 s and 5 s were applied to the beginning and end of the original record, respectively, before adding zero pads and filtering. For ease of comparison, only pad-stripped time series are shown.

A plot of response spectra can also be useful, in combination with the FAS and time series plots, in determining the filter corner frequency. Figure 13 shows both PSA and SD, the latter to

emphasize the sensitivity of the low-frequency portion of the spectrum to the filter corner. For ease in comparing with the FAS plot, I've used frequency rather than period on the abscissa. The plot was made using the output of *filt\_plot.for* for all but one of the response spectra; for the response spectra corresponding to the zoc acceleration I used *smc2rs.for*.

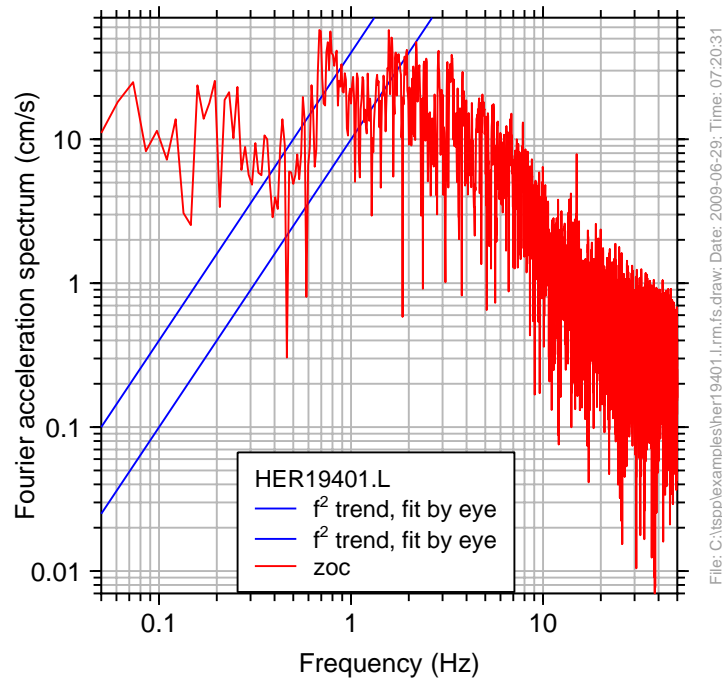


**Figure 13.** Response spectra for the zoc acceleration and for ten filters (only the response spectra for three of the filters are distinguished by color). Also shown are the spectra for the tapered and filtered time series---clearly tapering makes little difference in the response spectra.

It is not the purpose of this report to provide a detailed discussion of how to choose filter corner frequencies, but a few comments are in order. Because ground-motion records from moderate events usually have distinct P- and S-wave arrivals, it is not expected that long period oscillations will occur before the S-arrival (unless close to the fault, when near- and intermediate-field terms can produce such motions). Thus the pre-S oscillations seen in Figures 11 and 12 for filters less than about 0.719 are not expected on physical grounds. Note also that there is an increase in the FAS around 0.4 Hz which seems to produce the large SD at frequencies around 0.2—0.4 Hz for the records filtered with a fairly low filter frequency. As seen in the figure above, this peak in SD is very sensitive to the filter frequencies (not surprising, given that the filters start at 0.2 Hz and thus quickly eliminate the motions leading the low-frequency peak in SD). Based on all of the figures above, I would choose a filter corner between 0.719 and 0.928 Hz.

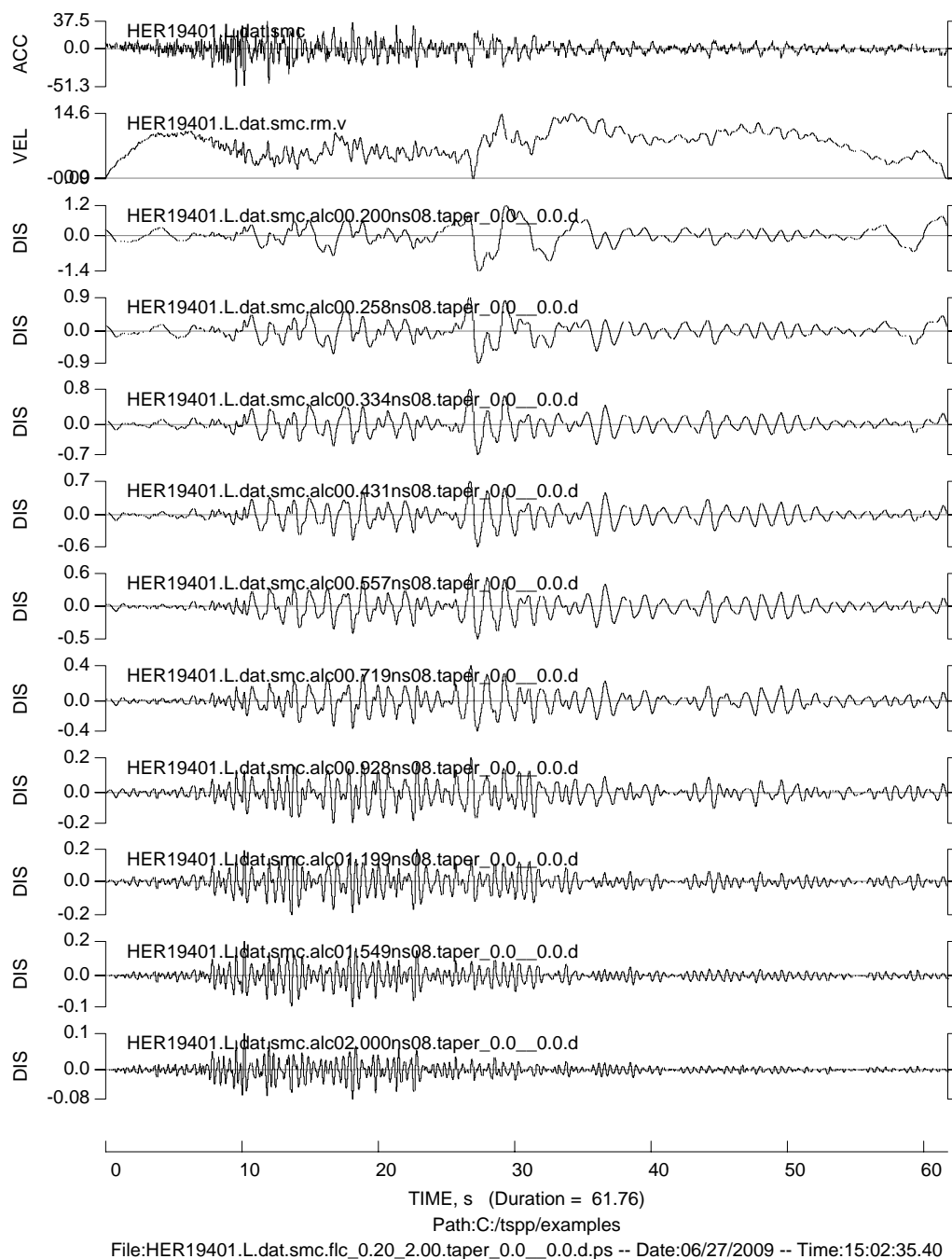
## A time series with a somewhat complicated Fourier acceleration spectrum

The second example used the record HER19401.L.dat.smc. This was recorded at an epicentral distance of 35 km from an **M** 6.1 earthquake at 90 km depth in Greece; the earthquake occurred on 23 May 1994. Figure 14 shows the FAS for the uncorrected record.

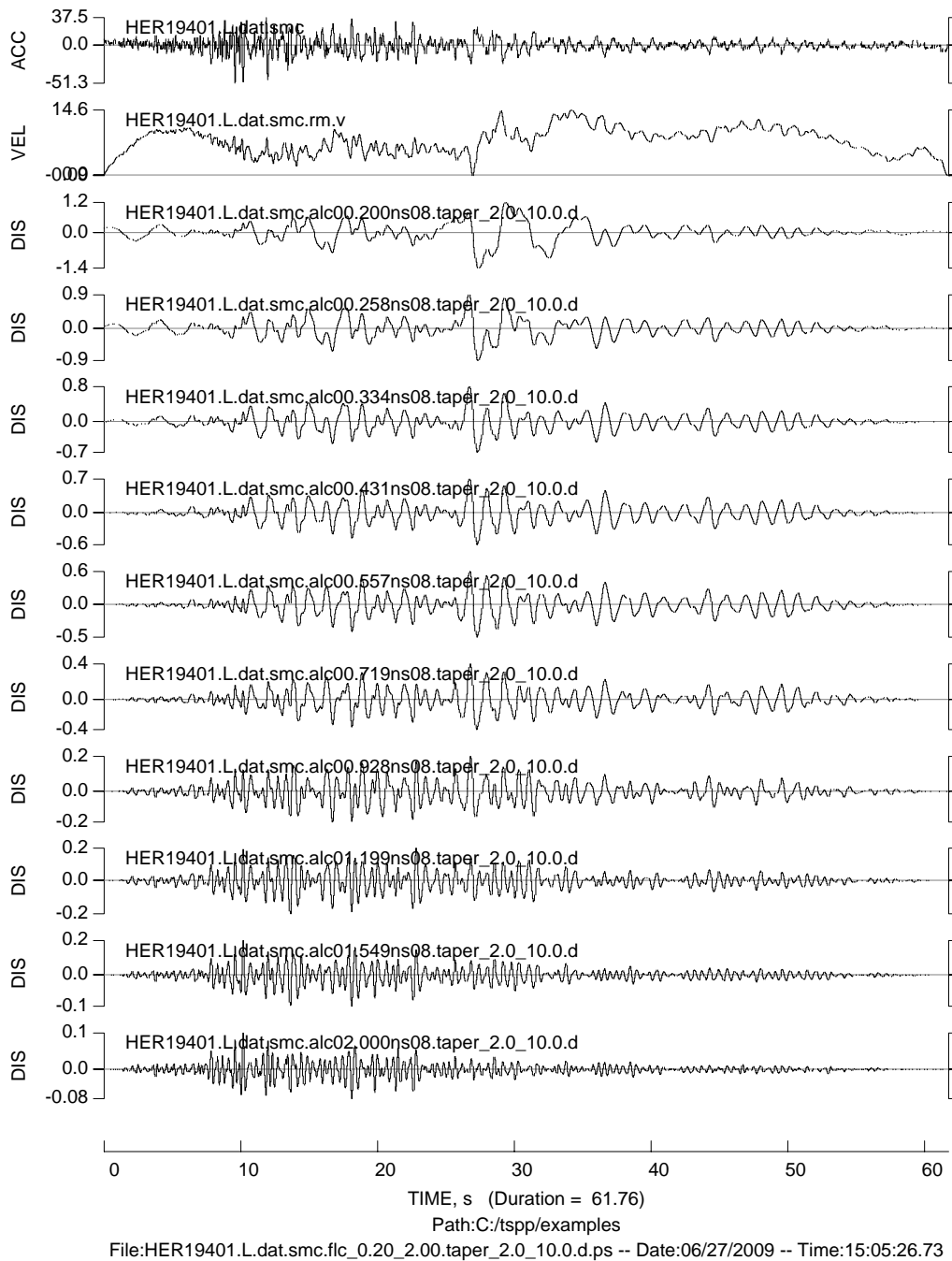


**Figure 14.** The FAS for the HER19401.L record (see the caption to Figure 10).

The spectrum for this event is considerably more complicated than for the previous event. In particular, there are two relative peaks in the FAS, one near 0.8 Hz and one near 1.5 Hz. Is the first one real? If so, the filter corner should be chosen less than 0.8 Hz. The displacement waveforms, with and without tapers, are shown in Figures 15 and 16.

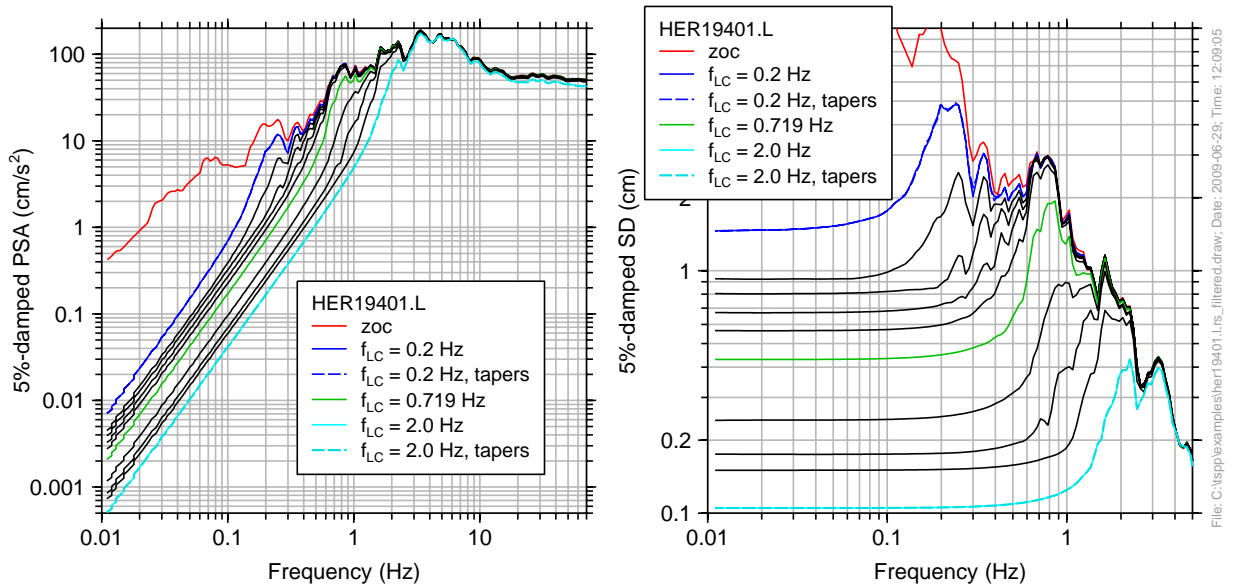


**Figure 15.** Filtered waveforms for the HER1940.L record (see Figure 11 caption for details).



**Figure 16.** Filtered waveforms for the HER1940.L record, when tapers have been applied (see Figure 12 caption for details).

Note the fairly long-period phase at about 27 s. This phase probably contributes to the relative increase in the FAS around 0.2 Hz (Figure 14) and to the strong peak in SD near 0.2 Hz (Figure 17, below).



**Figure 17.** PSA and SD for the HER19401.L record (see the caption to Figure 13 for details).

Is it the phase near 27 s real motion, or noise? It is hard to tell. It occurs well after the S-arrival and has a finite duration, as would be expected of a real phase. Also, as the event is deep and the recording station is on the island of Crete, there might be wave propagation effects associated with the subducting slab that will produce complexity in the recorded waveforms. On the other hand, there are other long-period oscillations throughout the record that might be due to noise. For this reason, I would choose a filter corner near 0.5 Hz. This will preserve the peak in SD around 0.8 Hz (note that filter corners of 0.719 Hz and higher strongly decrease the amplitude of the response spectrum around 0.8 Hz) but will eliminate the longer-period oscillations.

## A General Comment about using Padded Time Series

Fourier spectra, response spectra, and velocity and displacements of filtered data should always be computed from the complete, padded time series, not the pad-stripped data. Pad-stripped time series are often provided by data agencies, but ground-motion intensity measures such as peak velocity and response spectral amplitudes provided by the agencies are (or should be) obtained from the complete padded and filtered acceleration time series. It is inconsistent for the user to compute these ground-motion intensity measures from the pad-stripped acceleration time series (this also implies that using the pad-stripped acceleration time series for any analysis, such as the response of a nonlinear structure, is formally an inconsistent use of the time series).

## Acknowledgments

I thank Charles Muller for providing the Fortran source code for the original versions of several subroutines and Chris Stephens and Sinan Akkar for reviews of the report. John Douglas and Basil Margaris supplied the data used in the sample sessions. A number of these programs benefitted greatly from suggestions made by Chris Stephens; I give him credit for his suggestions in the modification logs contained at the end of the headers in each program, just before the beginning of the source code.



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